

IRRIGATION SCHEDULING

Water Balance Method

by

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Revised: March 3, 2014

1. DEFINITIONS

1.1 ET - evapotranspiration is a vaporization process where water experiences a phase change between a liquid and vapor. If the water vaporizes from the plant surface or soil surface the process is called evaporation. Water vaporizing inside the plant leaves and diffusing through the leaf pores to the ambient air is called transpiration. Evapotranspiration (ET) is the sum of evaporation (E) and transpiration (T).

1.2 ET_c - crop evapotranspiration is the maximum ET of a specified crop where the crop growth and production is not limited by water availability or plant stress.

1.3 ET_o - reference evapotranspiration is the ET of a hypothetical 12 cm tall vegetative surface with a fixed canopy resistance and the aerodynamic resistance an inverse function of the wind speed. It serves as a reference for calculating the ET_c of other crops. ET_o approximates the ET of a broad expanse of 12 cm tall cool-season (C-3 species) grass.

1.4 K_c - crop coefficient values are factors that are multiplied by ET_o to estimate ET_c . Whereas, ET_o accounts for weather variation, K_c factors account for crop morphology, crop physiology, and irrigation management.

1.5 ET_a - actual crop evapotranspiration is the ET of a specific crop, which can be less than ET_c when the crop experiences water or some other type of physiological stress. For most crops, production is reduced when the ET_a is less than ET_c . The main field crop exceptions are cotton, sugar beets, and canning tomatoes that can produce a more marketable yield when moderately water stressed during certain growth periods. This is also true for tree crops where the fruit is dried (e.g., prunes) and for wine grapes, where some stress improves grape quality. In addition, plant disease may be reduced with deficit irrigation in some crops.

1.6 θ_F - field capacity is the water holding capacity of a soil that has been saturated and then allowed to drain the excess gravitational water for 1-2 days. θ_F is typically expressed as a volumetric water content (m^3 of water per m^3 of soil) or as a depth of water per unit depth of soil (m of water per m of soil).

1.7 FC - water content at field capacity is the water content of a specified depth of soil when the soil is at field capacity (θ_F). For example, if a uniform 0.5 m depth of soil has $\theta_F=0.37 m m^{-1}$ (m of water per m depth of soil), then $FC=0.37 \times 0.5=0.185 m=185$ mm.

1.8 θ_p - permanent wilting point is the water holding capacity of soil at the permanent wilting point. The θ_p is expressed as a volumetric water content (m^3 of water per m^3 of soil) or as a depth of water per unit depth of soil (m of water per m of soil). It is the water holding capacity where a plant is expected to wilt and not recover when placed in an environment of 100% relative humidity. Although not strictly correct, the θ_p is commonly selected as the water holding capacity corresponding to 1.5 MPa of soil water tension (-1.5 MPa matric potential).

1.9 PWP - water content at the permanent wilting point is the water content of a specified depth of soil at the permanent wilting point (θ_p). For example, if a uniform 0.5 m depth of soil has $\theta_p=0.17 m m^{-1}$ (m of water per m depth of soil), then $PWP=0.17 \times 0.5=0.085 m=85 mm$.

1.10 θ_A - available water holding capacity is the water holding capacity of a soil between field capacity (θ_F) and the permanent wilting point (θ_p) or $\theta_A=\theta_F-\theta_p$.

1.11 AW - available water content is the water content of a specified depth of soil between FC and PWP ($AW = FC - PWP$). For example, if a uniform 0.5 m depth of soil has $\theta_F=0.37 m m^{-1}$ and $\theta_p=0.17 m m^{-1}$, then $\theta_A=0.20 m m^{-1}$ and $AW=0.20 \times 0.5=0.100 m=100 mm$. Also, $FC=0.185 m$ and $PWP=0.085 m$, so $AW=0.185-0.085=0.100 m=100 mm$.

1.12 PAW - plant available water is the water content within a crop rooting depth that can potentially be extracted by the plants. PAW is calculated by determining the available water holding content (AW) for each distinct soil layer and adding the AW values for all layers within the rooting depth.

1.13 SWC - soil water content is the quantity of stored water within a specified crop rooting depth. The SWC is equal to the water content at field capacity minus the soil water depletion ($SWC=FC-SWD$).

1.14 SWD - soil water depletion is the depletion or deficit of soil water below field capacity. The SWD is calculated as field capacity minus the soil water content ($SWD=FC-SWC$).

1.15 YTD - yield threshold depletion is the soil water depletion below field capacity where a crop begins to experience water stress that may reduce marketable yield (production and/or quality).

1.16 YT - yield threshold is the soil water content corresponding to the YTD ($YT=FC-YTD$). For irrigation scheduling, the goal is to maintain the SWC between the yield threshold (YT) and field capacity (FC).

1.17 MAD - management allowable depletion is the depletion of soil water from field capacity where irrigation is needed, based on production and management constraints

1.18 R_n - net radiation ($W m^{-2}$) is the balance of incoming and outgoing short and long wavelength radiation. It represents energy from radiation sources that are available to heat the soil, crop, and air and to vaporize water (ET). R_n is the main source of energy used to vaporize water and therefore it is the main weather factor affecting ET. In this syllabus, R_n is positive in the downward (from the sky) direction.

1.19 H - Sensible heat flux density ($W m^{-2}$) is the flux density of heat that you sense or feel. Sensible heat results from kinetic energy of air molecules moving and colliding at near sonic speeds. It is the heat that we measure with a thermometer. In this syllabus, H is positive away from the surface (upward to the sky).

1.20 λE or LE - Latent heat flux density ($W m^{-2}$) is the flux density of latent heat (heat stored in the hydrogen bonds of water) from a surface. From a crop surface, LE is the same as ET_a . In this discussion, LE is positive away from the surface (upward to the sky).

1.21 G - Soil heat flux density ($W m^{-2}$) is the flux density of heat into or out of the soil. G is positive downward from the surface (into the soil).

2. MANAGEMENT ALLOWABLE DEPLETION

Irrigation is timed using a management allowable depletion (MAD), which is the maximum soil water depletion (SWD) that is acceptable between irrigation applications. Irrigation events are usually timed so that applications are made the day before or after the SWD exceeds the MAD. The first step in determining the MAD is to identify the yield threshold depletion (YTD), which is the soil water depletion that is likely to reduce marketable yield if exceeded. Soil and plant characteristics are used to identify the YTD. Then other factors (e.g., irrigation method, water deliveries, cultural practices, labor constraints, etc.) are considered to determine the MAD. If possible, the MAD is selected to be less than or equal to the YTD.

2.1 Soil water retention

The relationship between soil water content and how tightly the water is held by the soil (soil matric potential) is typically described using a "soil water retention" curve. Three examples are shown in Figure 1. Soil matric potential is a negative number, and water is more attracted to the soil as the water content decreases and the matric potential becomes more negative (Fig. 1). Soil water tension is equal in magnitude but opposite in sign to the matric potential. Soil water tension is typically measured with a tensiometer or gypsum blocks, so the matric

potential can be determined by changing the sign of a tensiometer or gypsum block reading. In this syllabus, matric potential and soil water tension are expressed in pressure units (MegaPascals or MPa, where 1.0 MPa=10.0 Bars).

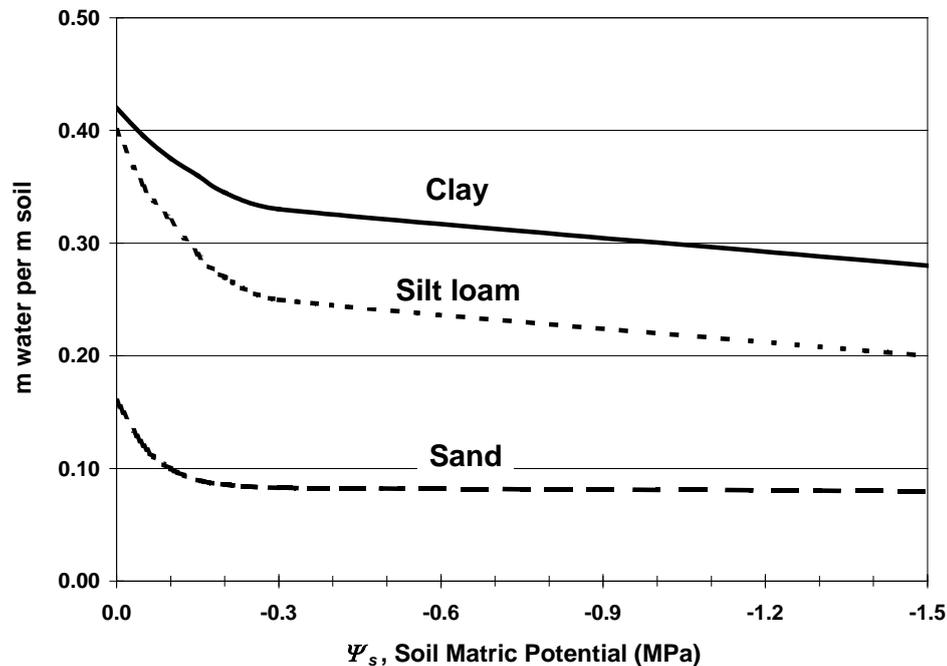


Figure 1. Hypothetical soil water retention curves for typical clay, silt loam, and sand soils.

2.2 Field capacity

Field capacity (θ_F) is the water holding capacity of a soil (m of water per m of soil depth) after excess water has drained from the soil; typically one or two days after an irrigation or rainfall. Each soil is unique, but θ_F typically falls between -0.01 MPa for light (sandy) and -0.033 MPa for heavy (clay) soils. FC is the water content of a uniform depth of soil at θ_F . If $\theta_F = 0.333$ m of water per m of soil depth within a uniform 0.30 m soil layer, then the water content at field capacity for the 0.30 m depth of soil is:

$$FC = 0.333 \text{ m water per m of soil} \times 0.30 \text{ m of depth} = 0.100 \text{ m} = 100 \text{ mm.}$$

2.3 Permanent Wilting Point

As a soil dries, the soil matric potential becomes more negative (water tension more positive), and it becomes more difficult for plant roots to extract water. At -1.5 MPa, the soil is said to be at the permanent wilting point (θ_P). Originally, the θ_P was defined as: “the soil water content at which a wilted plant will not recover when placed in an environment of 100% relative humidity.” However, a matric potential of -1.5 MPa is now commonly accepted as

the θ_p for irrigation scheduling purposes. The θ_p of a soil can be expressed in m of water per m of soil depth. Then the water content at θ_p for a uniform soil of known depth is determined by multiplying the θ_p in m of water per m of soil by the soil depth in m. For example, if $\theta_p = 0.167$ m of water per m of soil depth within a 0.30 m effective rooting depth, then the water content at the permanent wilting point is:

$$\text{PWP} = 0.167 \text{ m water per m of soil} \times 0.30 \text{ m of depth} = 0.05 \text{ m} = 50 \text{ mm.}$$

In Figure 1, note that most of the change in soil water content occurs between 0 and -0.1 MPa, and large decreases in soil matric potential result from small decreases in soil water content after falling below -0.1 MPa. As a result, most crops are irrigated before the soil water tension exceeds 0.1 MPa to avoid the risk of severe water stress.

2.4 Plant Available Water

The water holding capacity of a soil layer between θ_F , and θ_p is called the available water holding capacity (θ_A), expressed in m of water per m of soil depth ($\theta_A = \theta_F - \theta_p$). Figure 2 shows the approximate relationship between θ_A , θ_F , and θ_p for common soil textural classes.

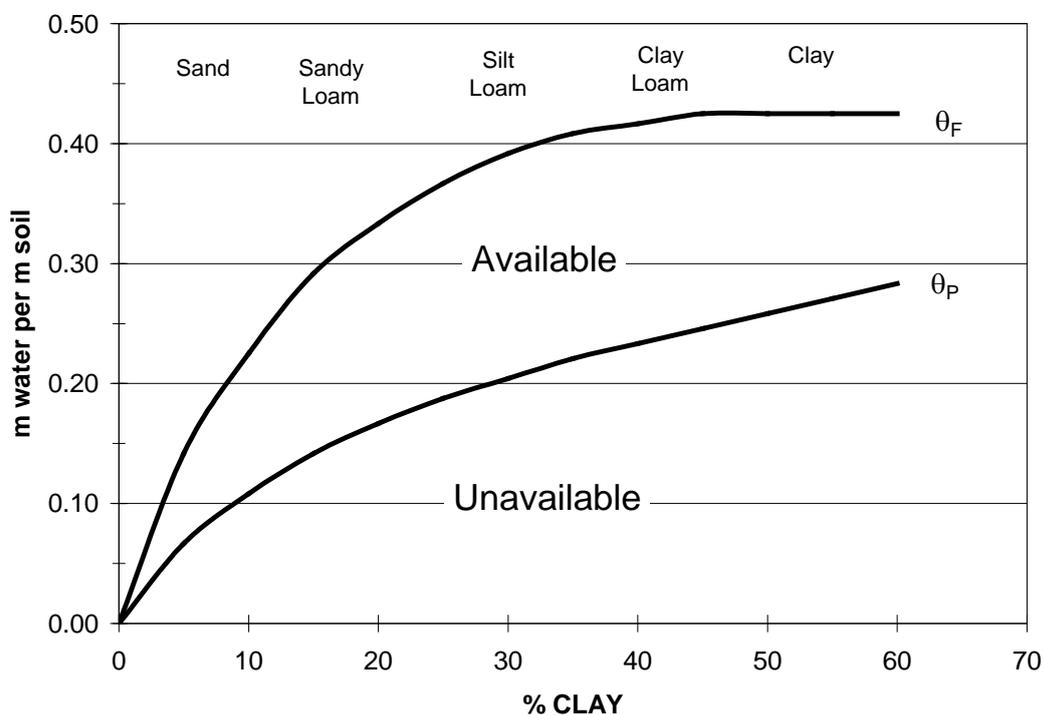


Figure 2. Approximate water-holding capacity of various soils as a function of % clay content. Appendix Table A.1 contains values for θ_F , θ_p , and θ_A for typical soil texture classes.

The water content held within a soil layer corresponding to θ_A is called the available water (AW). For example, if $\theta_A = 0.167$ m of water per m of soil depth within a 0.30 m effective rooting depth, then the available water content of the layer is:

$AW=0.167 \text{ m water per m of soil} \times 0.3 \text{ m of depth}=0.050 \text{ m}=50 \text{ mm}$.

Most soils have non-uniform water holding characteristics with depth, and water content values need to be calculated for several depths and totaled for the rooting zone to determine how much available water is in the root zone. The plant available water (PAW) is the sum of AW values within a crop's rooting zone. Therefore, $PAW=\sum AW_i$ for $i=1$ to n , where n is the number of uniform soil layers and AW_i is the available water in the i^{th} layer within the rooting depth. If the soil is uniform with depth, then $PAW = AW$ for the rooting depth.

Figure 3 shows how root growth affects AW during the season for a potato crop planted on a uniform soil on 1 February. The root depth increases linearly from 0 at planting to 0.2 m at the end of the initial growth period on 2 March and to 0.4 m at the end of rapid growth on 13 April. Then it remains at 0.4 m until the end of the season. Given the soil water holding capacities $\theta_F=0.4$ and $\theta_P=0.2$ m of water per m of soil, the water content values are $FC\approx 0.16 \text{ m}=160 \text{ mm}$, $PWP=0.080 \text{ m}=80 \text{ mm}$, and $AW=FC-PWP=0.080 \text{ m}=80 \text{ mm}$ for the 0.4 m soil layer.

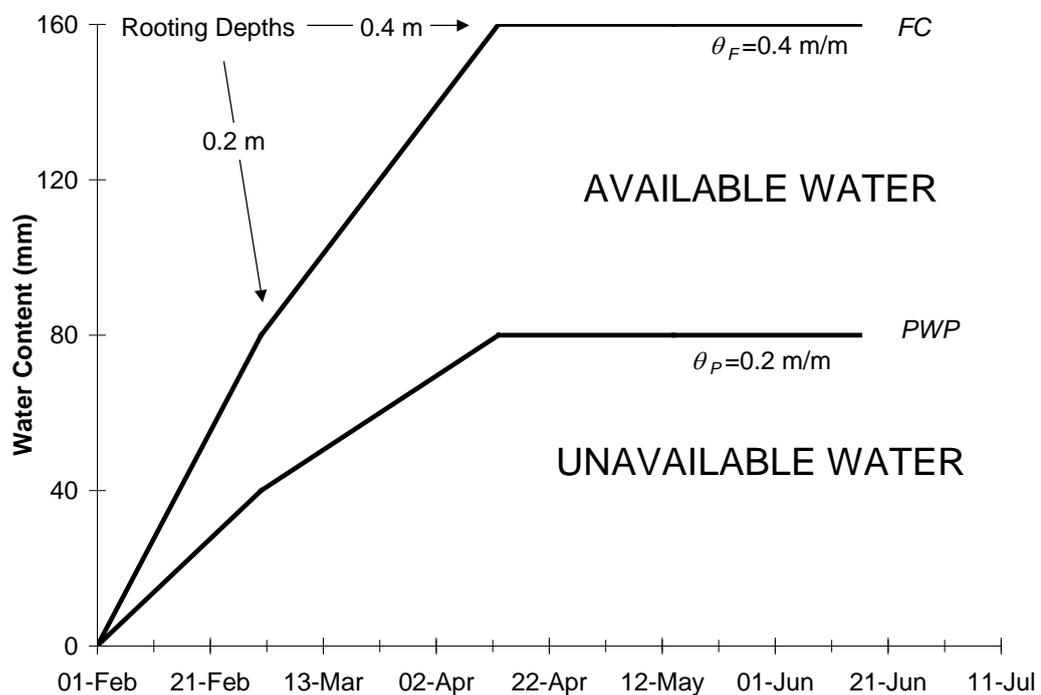


Figure 3. Plot of the change in available and unavailable water content as roots grow from 0.0 to 0.2 m during initial growth and from 0.2 m to 0.4 m during rapid growth of a potato crop.

2.5 Yield threshold depletion

The first step in determining the MAD is to identify the yield threshold depletion YTD, which is the soil water depletion that is likely to decrease marketable yield if exceeded. Field and

vegetable crops have growing roots and therefore the rooting depth increases during initial and rapid growth periods of the season. As the roots grow, PAW increases (Figure 4), and the YTD, which is a fraction of the PAW, can also be extended. The percentage of PAW that corresponds to the YTD is called the allowable depletion (AD). Values for AD are often changed during a season to account for sensitivity to water stress during critical developmental periods and for changes in rooting depth and evaporative demand.

Values to use for the AD are generally about 50% of the PAW or about 1/4 of FC within the effective rooting zone for many soils. Therefore, using a YTD equal to 1/4 of FC often gives good results. This is clear in Figure 4, which shows the FC, PWP, and YT for a soil with FC=160 mm. The dotted line representing the YTD is 50% of the PAW from date A through D. After date D, the percentage allowable depletion of the PAW is linearly increased to 100% of the PAW on date E, so the YTD increases from about 40 to 80 mm (the YT drops from 120 to 80 mm). Soils are often dried before harvesting a crop without significant loss of production or quality. Crops that are sensitive to water stress need an AD less than 50% and crops that are tolerant to stress can use a larger AD.

If low volume irrigation systems, which wet only part of the soil volume, are used, then the YTD should be adjusted appropriately. For example, if a drip system wets only 25% of the full soil volume, which is wetted by a sprinkler system, and the YTD for the sprinklers is: YTD=50 mm, then the adjusted YTD for the drip system is 25% of the full volume value or YTD = 12.5 mm.

For crops that are watered with pressurized irrigation systems, the MAD is typically set equal to the YTD. However, during the initial growth period, the MAD is often fixed at the same value as the YTD on date B. For high value vegetable crops, frequent irrigation during initial growth is used for good emergence and the MAD selection is not important. The goal should be to keep the soil wet, but not waste too much water. For many of the agronomic field crops, irrigation is not applied during the initial growth period, so the setting the MAD equal to the YTD on date B poses no problem.

For crops watered by surface irrigation methods, the MAD is typically selected to achieve good application uniformity and efficiency. Based on the application rate (AR) and the runtime (RT), the gross application corresponding to optimal efficiency is calculated as:

$$GA = AR \times RT \quad (1)$$

The optimal MAD is calculated by accounting for the application efficiency (AE), which is the fraction of water applied that will be stored in the root zone for use in evapotranspiration.

$$MAD = GA \times AE \quad (2)$$

where the AE is expressed as a fraction. The MAD for surface irrigated crops is often different from the YTD. However, if the YTD is less than the calculated MAD, the system should be improved to avoid yield reducing water stress, which may occur.

Although Figure 3 illustrates the relationship between FC, PWP, and PAW it is better to show the water content relationships on a scale from 0 to FC, where FC is the maximum rooting depth during the season as shown in Figure 4. Then all calculations are made relative to the water content within the maximum effective root zone. Displaying the water content information in this manner facilitates irrigation scheduling because soil water content measurements are directly comparable with the calculated daily water balance and it is easier to account for stored soil water contributions, effective rainfall, etc. In other words, it is easier to correct estimated values with soil water content measurements (e.g., from a neutron probe).

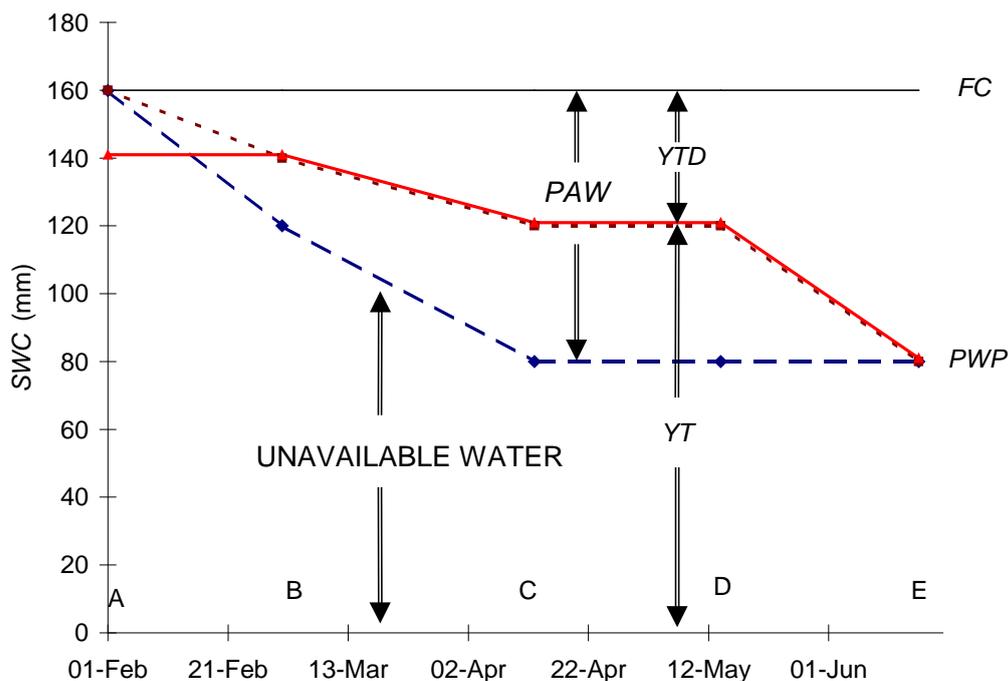


Figure 4. A plot soil water content (SWC) versus time indicating the change in the plant available water (PAW) and the yield threshold depletion (YTD) relative to a fixed FC=160 mm at the maximum root depth. Data are the same as those used in Fig. 3. Note that the yield threshold is $YT=FC-YTD$. The initial growth period is from date A to B, the rapid growth period is from B to C, midseason is from C to D, and late season is from D to E.

Determination of PAW for tree and vine crops is similar to the field crop calculations except the rooting depths are typically assumed to be constant after attaining maturity (about 62% ground shading). However, the rooting depth measurements for immature tree and vine crops are needed to estimate the effective root zone depth. Although the actual root depth of mature tree and vine crops change little during a season, the effective root depth may be affected by soil temperature, disease or other factors. In some cases, cold soil temperature

can impede water uptake by roots and the effective rooting depth could be less than the measured rooting depth.

2.6 Management allowable depletion

Ideally, the MAD should be less than or equal to the YTD. However, sometimes this may not be possible because of limitations of the irrigation method, water delivery, pump capacity, etc. For example, water may only be available from the water district on a fixed schedule. Another problem is that often a fixed set time is needed for surface irrigation methods to evenly distribute water over a field. If so, adjust your choice for the MAD appropriately. In some cases, the choice for MAD will be bigger than the YTD. If this is the situation, the options are to change the crop, change the irrigation method, change the distribution system, or accept a lower marketable yield. In some cases, the yield loss may be insignificant.

For crops, the MAD will change during the season because (1) the effective rooting depth changes, (2) soil infiltration rate decreases, (3) water stress is needed to improve marketability of the crop, or (4) the irrigation method changes. Once the MAD values are identified, the procedure is to monitor soil water content using water balance calculations. Then, when the soil water depletion ($SWD = FC - SWC$) is expected to exceed the MAD, the crop is irrigated with the net amount ($NA = SWD$) to return the water content of the soil to near field capacity (FC). Applications less than $NA = SWD$ are possible, but then the soil water content will be uneven, application efficiency will be unknown, and timing of future irrigation will be difficult to determine. The gross application (GA) for the irrigation accounts for irrigation application efficiency (AE) as well. Application efficiency is the percentage of water applied that is likely to contribute to crop evapotranspiration (ET_c). The GA is calculated as: $GA = \frac{NA}{AE}$; where AE is expressed as a fraction.

3. WATER BALANCE SCHEDULING

One of the more widely promoted procedures for irrigation scheduling is the water balance technique. The method involves maintaining a favorable soil water balance by monitoring all additions and losses of a field's water. Often referred to as evapotranspiration or ET scheduling, the most important component of the water balance is an accurate estimate of crop water use. The water balance method can be especially useful with low volume (i.e., high frequency) irrigation methods (e.g., drip or micro-sprinkler) where small amounts of water are frequently applied. Because many of the components are estimated, a good field-check program (i.e., monitoring with tensiometers, gypsum blocks, neutron probes, etc.) is recommended to test that the calculations are correct.

The natural sources of water for a crop include precipitation, stored soil water, water tables and fog interception. If the natural sources are not adequate to supply sufficient water to avoid yield reducing water stress, irrigation water is added as a supplement. When calculating an irrigation schedule, all of the sources and losses of water are measured or estimated to estimate changes in soil water content. In this section, the calculations used to

make a water balance irrigation schedule are discussed. In addition, methods to estimate the natural water supply (effective rainfall, stored soil water, and fog interception) and the crop water losses (evapotranspiration) are explained. Methods to evaluate irrigation systems and estimate water losses to runoff and deep percolation are discussed in another section. At the end of this section, you should be able to use the water balance technique to make an irrigation schedule for major crops.

3.1 Energy Balance

Energy is the driving force determining evapotranspiration (ET) rates for unstressed crops and; therefore, understanding energy balance is critical to understanding ET. Energy is needed to break the hydrogen bonds and separate H₂O molecules from the liquid water. The energy for ET comes mainly from radiation although heat transfer from the air and soil can also contribute to ET. The key to understanding ET is to understand how much energy is available within the crop canopy to evaporate water.

The energy balance of a crop canopy is expressed using the following equation:

$$R_n = G + H + LE \quad (3)$$

where R_n is net radiation, G is soil heat flux density, H is the sensible heat flux density, and LE is latent heat flux density. The small amount of energy used in photosynthesis and stored in the biomass is disregarded. This is the equation that is typically used by meteorologists and physicists. In this equation, R_n is considered to be a positive source of energy when energy is being transferred to the surface and G , H , and LE are considered positive away from the surface. Therefore, the R_n is partitioned into G , H , and LE and a plot of a daytime energy balance will typically show positive values. Equation 4 is used in this syllabus. In some literature, you will see the following equation:

$$R_n + G + H + LE = 0 \quad (4)$$

In this equation, R_n , G , H , and LE are all considered positive towards the surface. In a plot of typical daytime values, the R_n curve will plot above zero and the other curves will plot below zero. Equation 4 will not be used in this syllabus. It is only presented to help avoid confusion when reading other literature on energy balance.

Regardless of which equation is used, the concepts of energy balance are the same. In either case, when there is no wind, the main source of energy (R_n) is partitioned into G , H , and LE . When there is wind blowing in warm air (warm air advection), horizontal movement of the air brings additional sensible heat to the canopy and provides another source of energy in addition to R_n for evaporation. The additional heat, due to advection, will have little effect on R_n , but it will increase the amount of heat supplied to LE and G . When there is advection, the value for H decreases and the value for LE is increases. Under strong warm air advection, when considerably warmer air blows over a cooler crop, H becomes negative and LE can be

bigger than R_n . The most important factor to remember about energy balance is that the actual measured values for R_n , G , H , and LE must balance in all situations.

Net radiation (R_n) is the main source of energy for ET. Net radiation is the net amount of radiative energy from short- and long-waveband radiation. Net radiation is calculated as:

$$R_n = R_{s_d} + R_{s_u} + L_d + L_u = (1 - a)R_s + L_d + L_u \quad (5)$$

where the R_{s_d} and R_{s_u} are incoming and outgoing solar (short-waveband) radiation, L_d and L_u are incoming and outgoing terrestrial (long-waveband) radiation, and a is the albedo or reflection of short wave radiation from the surface. Recall that downward radiation has a positive and upward radiation a negative sign. The factors that determine difference in net radiation between crops and other surfaces at the same time are mainly the R_{s_u} , which is affected by the albedo (reflection) of solar radiation from the surface, and the L_u , which is affected by the temperature of the surface. If R_{s_u} is greater because the surface has a bigger albedo, then the net radiation is less. If surface temperature is greater, then L_u is bigger and the R_n is less. If the surface temperature is lower, then L_u is less and R_n is bigger.

The air has mass and the total heat content of the air includes both sensible heat and latent heat. Sensible heat is the heat that you sense by measuring with a thermometer and latent heat is energy that is stored in hydrogen bonds of water molecules. Sensible heat is transferred to or away from the surface because of vertical air movement (natural or forced convection) or because of horizontal air movement (advection). The vertical transfer of heat is called sensible heat flux density (H). This vertical transfer introduces or removes heat from a crop surface and can affect the amount of heat available to vaporize water. In this syllabus, H is positive away from the surface, when heat is added to the air, and negative towards the surface, when heat is removed from the air.

The soil also has a temperature and therefore contains sensible heat. Transfer of this heat per unit surface area is called soil heat flux density (G). Heat is transferred into the soil when the soil surface is warmer than below and it is transferred upward to the soil surface if the soil below is warmer. Then the heat from the soil surface can contribute to (1) vaporization of soil surface water, (2) heating the plant canopy by radiation from the surface, or (3) warming the air and plants by convection of sensible heat to the canopy. In this syllabus, soil heat flux density is positive when the flux is downward from the surface (downward), when the soil is heating, and it is negative towards the surface (upward), when the soil is cooling.

The other energy to consider in an energy balance is the energy contained in the hydrogen bonds of water vapor. The amount of energy used to break hydrogen bonds and vaporize water depends on the number of water molecules evaporated. The energy is called "latent heat" because it is chemical energy that is latent while in water vapor form but changes to sensible heat when the water vapor condenses as liquid water. The latent heat flux density is the amount latent energy per unit time per unit area transferred vertically away from or towards the surface. Latent heat flux density is determined by multiplying the grams of water

that are vaporized per square meter of surface area per second (E) by the latent heat of vaporization (L); that is, L is the number of Joules needed to evaporate one gram of water.

In this syllabus, latent heat flux density is positive when evaporation is occurring, when latent heat is added to the air, and the flux is away from the surface (upward). The flux is negative when condensation is occurring, when latent heat is lost from the air, and the flux is toward the surface (downward).

3.2 Humidity

When more hydrogen bonds are broken than form on a wet surface, then more water molecules are leaving than attaching and the latent heat flux density will be positive (away from the surface). In an environment with higher absolute humidity, more water molecules will strike and attach to the water surface than in a less humid environment. When the water molecules attach to the surface, latent heat is converted to sensible heat and the temperature rises. Therefore, a wet surface in an environment with higher absolute humidity will have more condensation and conversion from latent to sensible heat at the surface. Therefore, the wet surface will be warmer in a humid than in an arid environment. Since the wet surface is cooler in an arid environment, sensible heat transfer from the air will be greater than in a humid environment. This leads to more energy for vaporization and higher evapotranspiration rates in the arid environment.

Clearly, an appreciation for humidity concepts is a useful for understand ET. Equations for converting humidity expressions are discussed below, and a chart showing the relationships between some humidity variables is provided in Figure 5. The following are useful definitions:

- Vapor pressure (e) is the partial pressure exerted by water vapor in the atmosphere. Vapor pressure is a measure of the water vapor content of the atmosphere and it has the units: Pascals (Pa) or Kilopascals (kPa).
- Saturation vapor pressure (e_s) is the pressure exerted by water vapor in air that is saturated with respect to a flat surface of pure water. At saturation, the number of water molecules evaporating from the flat surface is equal to the number vaporizing from the surface. Saturation vapor pressure is approximately an exponential function of temperature (T) and the following equation from Tetens (1930) is often used:

$$e_s = 0.6108 \exp\left(\frac{17.27T}{T + 237.3}\right) \quad (6)$$

where exp is the exponential function (e^x).

- Barometric pressure (P_B) is the pressure exerted by all gases in the atmosphere, expressed in kPa. Barometric pressure can be estimated from elevation in meters above mean sea level (E_L) using the following equation from Burman et al. (1987).

$$P_B = 101.3 \left(\frac{293 - 0.0065 E_L}{293} \right)^{5.26} \quad (7)$$

- Dry-bulb temperature (T) is the temperature that is measured with an aspirated thermometer and is same as the air temperature.
- Wet-bulb temperature (T_w) is the temperature measured with an aspirated thermometer with the bulb covered by a wet cotton wick. T_w is an approximation for the thermodynamic wet-bulb temperature, which is the temperature obtained when water is evaporated into the air until the air becomes saturated without changes in the total heat content (enthalpy) of the air and the barometric pressure. When water is evaporated into the air, the vapor pressure rises causing the dew point temperature to increase. Sensible heat is removed from the air to evaporate the water causing the air temperature to decrease. As the air becomes saturated, the dew point and air temperatures converge to the wet bulb temperature. The vapor pressure of air is a function of the wet bulb temperature, dry bulb temperature, and barometric pressure:

$$e = e_w - 0.000660(1 + 0.00115T_w)(T - T_w)P_B \quad (8)$$

where all of the pressures are in kPa and e_w is the saturation vapor pressure at the wet bulb temperature:

$$e_w = 0.6108 \exp\left(\frac{17.27T_w}{T_w + 237.3}\right) \quad (9)$$

- Relative humidity (RH) is the ratio of vapor pressure to saturation vapor pressure expressed as a percentage

$$RH = 100 \left(\frac{e}{e_s} \right) \quad (10)$$

Relative humidity is a function of water vapor content of the air and the air temperature. When T increases, at fixed e , RH decreases. When e increases, at fixed T , RH increases.

- Dew point temperature (T_d) is the temperature at which air becomes saturated with water vapor if the air is cooled without changing enthalpy or barometric pressure. The vapor pressure of the air is equal to the saturation vapor pressure of air at the T_d . Therefore, the vapor pressure (e) is calculated from T_d as:

$$e = 0.6108 \exp\left(\frac{17.27T_d}{T_d + 237.3}\right) \quad (11)$$

When the water vapor content (e) of the air increases, then T_d increases.

- Vapor pressure deficit (VPD) is the difference between saturation vapor pressure and vapor pressure:

$$VPD = e_s - e. \quad (12)$$

VPD is a function of water vapor content of the air and the air temperature. When T increases and e is fixed, e_s and VPD increase. When e increases and T is fixed, then VPD decreases.

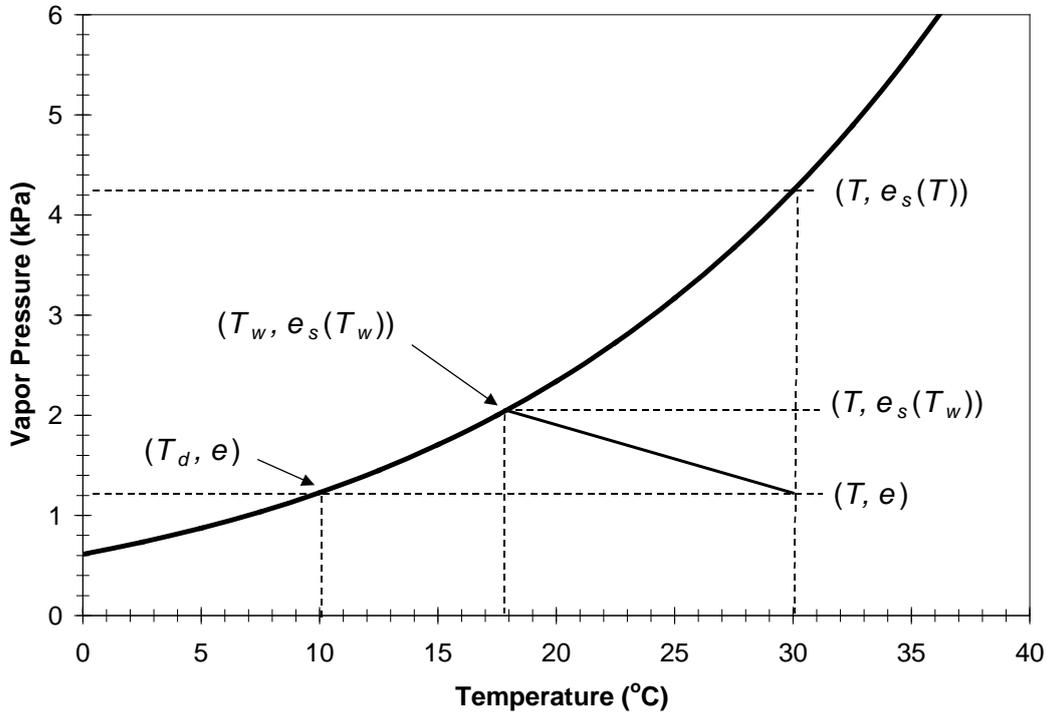


Figure 5. A psychrometric chart showing the relationship between temperature (T), vapor pressure (e), wet-bulb temperature (T_w), dew point temperature (T_d), and saturation vapor pressure $e_s(T)$ and $e_s(T_w)$. Relative humidity (%) is calculated as $RH = 100 \left(\frac{e}{e_s(T)} \right)$, and vapor pressure deficit in kPa is calculated as $VPD = e_s(T) - e$. In this example, $T=30^\circ\text{C}$, $T_w=17.8^\circ\text{C}$, $T_d=10^\circ\text{C}$, $e=1.23$ kPa, $e_s(T)=4.24$ kPa, $RH=29\%$, and $VPD=3.01$ kPa.

3.3 Evapotranspiration

The main losses of water from an irrigated crop include surface and subsurface runoff, deep percolation, and ET_a . If the irrigation is managed well, most water loss from the field results from actual crop evapotranspiration (ET_a). Runoff and deep percolation losses are considerably smaller and they are normally estimated by performing a system evaluation during an irrigation event. Then the measured efficiency, from the system evaluation, is assumed to remain approximately the same in future irrigation. If the management or application amounts are changed, a new evaluation should be performed.

Maximum crop evapotranspiration (ET_c) is calculated as the product of reference evapotranspiration (ET_o) and a crop coefficient (K_c). ET_o is the evapotranspiration of a reference crop and the K_c is a crop factor. It is assumed that ET_o adjusts ET_c for variations in the weather and the K_c accounts for crop and management factors that cause ET_c to be different from ET_o . Reference evapotranspiration is the ET of a broad expanse of short vegetation with a specified canopy resistance (r_c) and aerodynamic resistance (r_a), which is a function of the wind speed measured at 2 m height above the ground. While the vegetation for ET_o is not specified, ET_o approximates the ET of a 12 cm tall, unstressed, cool-season (C-3 species) grass. In some locations, a 50 cm tall reference crop with fixed canopy and aerodynamic resistance is used for reference evapotranspiration, and it is given the symbol ET_r . The ET_r values approximate the ET of a 50 cm tall alfalfa crop.

The method that is currently recommended for calculation of ET_o using monthly or daily climatic data is the modified Penman-Monteith equation (Allen et al., 1998). Although less accurate, another method using monthly mean high and low daily temperatures (Hargreaves and Samani, 1982; 1985) is also presented as an alternative for use where only temperature data are available. In many locations, automated weather station networks are used to estimate ET_o using hourly weather data, and an hourly modified Penman-Monteith equation (ASCE-EWRI, 2005) is then recommended for ET_o calculations. Each of these methods will be presented.

3.3.1 Penman-Monteith Method

The Penman-Monteith method (Monteith and Unsworth, 1990) is a modification of the original Penman (1948) method.

$$LE = \frac{\Delta(R_n - G) + \rho C_p \left(e_s(T) - e \right) / r_a}{\Delta + \gamma(1 + r_c / r_a)} \quad (13)$$

where Δ is the slope of the saturation vapor pressure curve at mean daily air temperature (T), R_n and G are the net radiation and soil heat flux density, γ is the psychrometric constant, ρ is the density of air, C_p is the specific heat of air at constant pressure, $e_s(T)$ is the saturation vapor pressure at temperature T , e is the actual mean daily vapor pressure, r_a is the aerodynamic resistance to vapor transfer, and r_c is the canopy resistance to vapor transfer. Equation 13 is actually for the determination of near instantaneous LE.

A simplified Penman-Monteith (Allen et al., 1998; ASCE-EWRI, 2005) is widely used for ET_o calculations. The monthly and 24-hour Penman-Monteith equation for reference evapotranspiration (ET_o) in mm d^{-1} is:

$$ET_o = \frac{0.408\Delta(R_n - G) + \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (14)$$

where Δ is the slope of the saturation vapor pressure curve

$$\Delta = \frac{4098 \left[0.6108 \exp\left(\frac{17.27T}{T + 237.3}\right) \right]}{(T + 237.3)^2} \quad (15)$$

in kPa °C⁻¹ at the mean daily air temperature (T) in °C. The mean daily air temperature is calculated from the maximum and minimum daily temperature expressed in °C as:

$$T = \frac{T_x + T_n}{2} . \quad \gamma \text{ is the psychrometric constant}$$

$$\gamma = 0.665 \times 10^{-3} P \quad (16)$$

in kPa °C⁻¹. Using Eq. 7, P is the barometric pressure in kPa. R_n is the measured or estimated net radiation in MJ m⁻²d⁻¹. G is the soil heat flux density in MJ m⁻²d⁻¹. For 24-hour calculations,

$$G = 0 \quad (17)$$

and for monthly calculations

$$G = 0.07(T_{mon,i+1} - T_{mon,i-1}) \quad (18)$$

where $T_{mon,i+1}$ and $T_{mon,i-1}$ are the mean temperatures for the next and the previous month, respectively. The mean saturation vapor pressure (e_s) for the day is calculated as:

$$e_s = 0.5 \left[0.6108 \exp\left(\frac{17.27T_x}{T_x + 237.3}\right) + 0.6108 \exp\left(\frac{17.27T_n}{T_n + 237.3}\right) \right] \quad (19)$$

using the maximum (T_x) and minimum (T_n) daily air temperature expressed in °C. The mean daily actual vapor pressure (e_a) is calculated as:

$$e_a = 0.6108 \exp\left(\frac{17.27T_d}{T_d + 237.3}\right) \quad (20)$$

from the mean daily dew point temperature (T_d) expressed in °C or as:

$$e_a = 0.5 \left(0.6108 \exp \left(\frac{17.27 T_n}{T_n + 237.3} \right) \frac{RH_x}{100} + 0.6108 \exp \left(\frac{17.27 T_x}{T_x + 237.3} \right) \frac{RH_n}{100} \right) \quad (21)$$

from the minimum temperature and maximum relative humidity (RH_x) and the maximum temperature and minimum relative humidity (RH_n). The wind speed (u_2) expressed in $m s^{-1}$ can be measured at 2 m height or estimated as:

$$u_2 = u_z \frac{4.87}{\ln(67.8z - 5.42)} \quad (22)$$

where u_z is the wind speed in $m s^{-1}$ measured at height z in meters above the ground. The main difference between the monthly and daily (24-hour) calculations is that the monthly means of daily variables are used for the monthly calculation and G is calculated differently using equations 17 and 18. Because R_n is usually not measured, it must be estimated. The procedure to estimate R_n for monthly and for 24-hour data is presented in FAO 56 and ASCE-EWRI (2005).

3.3.2 Hargreaves Method

Sometimes only temperature data are available to estimate ET_o . Hargreaves and Samani (1982; 1985) reported a method to estimate daily ET_o using monthly means of daily maximum and minimum temperature data and estimated extra-terrestrial radiation (R_a). The procedure to estimate R_a is provided in Allen et al. (1998) and ASCE-EWRI (2005). This equation is not recommended for calculation of ET_o on a daily basis because variations in wind and humidity are not taken into account. However, the monthly mean calculations are reasonably accurate for planning irrigation schemes in all but extreme climates.

Evapotranspiration (ET_o) is calculated as:

$$ET_o = \frac{0.0023}{\lambda} R_a \sqrt{T_R} (T_M + 17.8) \quad (23)$$

where (T_R) is the monthly mean daily temperature range.

$$T_R = T_x - T_n \quad (24)$$

T_M is the monthly mean of daily temperature.

3.3.3 Hourly Penman-Monteith Method

The hourly Penman-Monteith equation as recommended in ASCE-EWRI (2005) is:

$$ET_o = \frac{0.408\Delta(R_n - G) + \frac{37}{T + 273}u_2(e_s - e_a)}{\Delta + \gamma^*} \quad (25)$$

where ET_o is in mm h^{-1} , R_n and G terms are in $\text{MJ m}^{-2}\text{h}^{-1}$, T is the hourly mean temperature ($^{\circ}\text{C}$), u_2 is the hourly mean wind speed in m s^{-1} , and the other variables are calculated using hourly mean variables. Use Eq. 22 to adjust wind speed measurements to $z=2.0$ m height. The saturation vapor pressure in kPa is:

$$e_s = 0.6108 \exp\left(\frac{17.27T}{T + 237.3}\right) \quad (26)$$

The mean actual vapor pressure (e_a) is calculated from T in $^{\circ}\text{C}$ and the mean relative humidity (RH) in % as:

$$e_a = e_s \left(\frac{RH}{100}\right) \quad (27)$$

The slope of the saturation vapor pressure curve (Δ) in $\text{kPa } ^{\circ}\text{C}^{-1}$ at the mean air temperature is calculated as:

$$\Delta = \frac{4098 \left[0.6108 \exp\left(\frac{17.27T}{T + 237.3}\right) \right]}{(T + 237.3)^2} \quad (28)$$

The psychrometric constant (γ) is again calculated as:

$$\gamma = 0.665 \times 10^{-3} P \quad (29)$$

using Eq. 7 for the barometric pressure (P). For the hourly equation, G is estimated as $G = 0.1R_n$ for $R_n \geq 0$ and as $G = 0.5R_n$ for $R_n < 0$.

The modified psychrometric constant is $\gamma^* = \gamma(1 + 0.34u_2)$ for the 24-hour Penman-Monteith equation. The $0.34u_2$ comes from the ratio of canopy to aerodynamic resistance (r_c/r_a), which is estimated as:

$$\frac{r_c}{r_a} = \frac{70}{208/u_2} = 0.34u_2 \quad (30)$$

for a 0.12 m tall, cool-season grass canopy. Using $r_c=70 \text{ s m}^{-1}$ gives good results when using 24-hour or monthly data, but errors result when using hourly data. A new recommendation to use 50 s m^{-1} , when $R_n \geq 0$ and plant stomata are fully open, and to use 200 s m^{-1} , when $R_n < 0$ and plant stomata are closed (ASCE-EWRI, 2005). This means that the values for γ^* will be:

$$\gamma^* = \gamma(1 + 0.24u_2) \quad (31)$$

when $R_n \geq 0$ and

$$\gamma^* = \gamma(1 + 0.96u_2) \quad (32)$$

when $R_n < 0$.

The biggest difficulty in calculating hourly ET_o is to estimate R_n . This is too complicated to include in this syllabus, but the procedures are given in ASCE-EWRI (2005).

3.4 Crop Coefficients

Crop coefficient (K_c) factors are numbers that are multiplied by ET_o to estimate crop evapotranspiration (ET_c), where ET_o approximates the ET_c for a broad expanse of unstressed, 0.12 m tall, cool-season grass. Because the grass is a uniformly dense canopy that transpires at a high rate, the ET_o goes up and down mainly as the energy available for evaporation increases and decreases. ET_c goes up and down as evaporative demand changes, but it is affected by crop morphology, crop physiology and irrigation frequency. Crop coefficients are determined by measuring ET_c . Then the K_c is calculated by dividing the result by measurements or ET_o estimates. Therefore, a K_c is used to adjust ET for differences between an unstressed crop and that of a broad expanse of unstressed grass. Thus ET_o accounts for weather effects on ET_c and the K_c accounts for crop factors and management.

In this syllabus, the K_c method uses linear interpolation between values at the ends of specific growth periods. It is assumed that the K_c for a particular crop at a known growth and development stage will be the same in the future if the environmental and management conditions are similar to those when the K_c was determined.

3.4.1 Bare Soil Evaporation

Crop coefficient (K_c) values depend on many different factors including the evaporation from bare soil, which is determined by the accumulated evaporative demand since the soil was last wetted and soil hydraulic properties. Assuming the soil has typical soil hydraulic properties, the K_c value depends on the number of days between wetting by irrigation or rainfall and the average evaporative demand (i.e., ET_o rate) during the period. Either Figure 6 or the equations presented in this section is used to determine the K_c value.

The crop coefficient curves for bare soil were developed with equations for estimating cumulative soil evaporation (CE_s) using the maximum possible cumulative soil evaporation (CE_x) and a soil hydraulic factor $\beta=2.6$. The β factor is soil specific and depends on the rate of water transfer through an unsaturated soil surface layer. However, the value $\beta=2.6$ is believed to be a typical value. For each value of ET_o in Fig. 1, the cumulative ET_o (CET_o)

was calculated as $CET_o = n \times ET_o$ for "n" days. The maximum possible soil evaporation on each day (E_x) was estimated as $E_x = ET_o \times K_x$ where

$$K_x = 1.22 - 0.04ET_o. \quad (33)$$

Then the cumulative maximum soil evaporation (CE_x) was calculated by adding the E_x values for the given number of days. When $\sqrt{CE_x} < \beta$, then

$$CE_s = CE_x, \quad (34)$$

and when $\sqrt{CE_x} \geq \beta$, then

$$CE_s = \beta\sqrt{CE_x}. \quad (35)$$

The crop coefficients for near-bare soil for each combination of ET_o and number of days between wettings were calculated as:

$$K_c = \frac{CE_s}{CET_o}. \quad (36)$$

Using Figure 6 and the monthly mean days between rainfall and monthly mean ET_o rates from Table 1, a sample annual K_c curve for nearly-bare soil is shown in Figure 7. A cubic- spline curve fit was used to estimate the days between rainfall and the daily ET_o rates for each day of the year. Daily values were used with the Eqs. 31-34 to estimate the daily K_c values for nearly-bare soil.

Table 1. Mean monthly rainfall frequency (days between rainfall) and ET_o rate (mm d^{-1}) used to determine daily rainfall frequency (R_nF) and ET_o for the examples in this syllabus.

Var	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
R_nF	6	9	16	30	31	30	31	31	30	16	10	8
ET_o	1.3	2.0	3.0	4.3	5.6	6.6	7.1	6.4	4.8	3.3	1.8	1.3

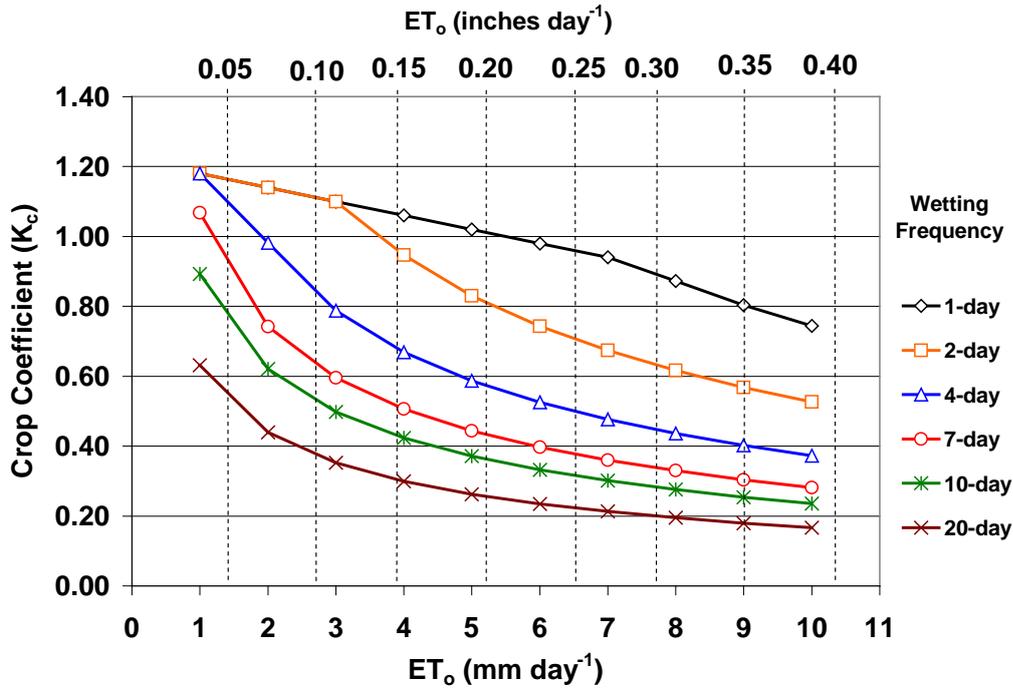


Figure 6. Crop coefficient (K_c) for near-bare soil (less than 10% ground cover) as a function of daily mean ET_0 rate and days between significant rainfall or irrigation (>5.0 mm).

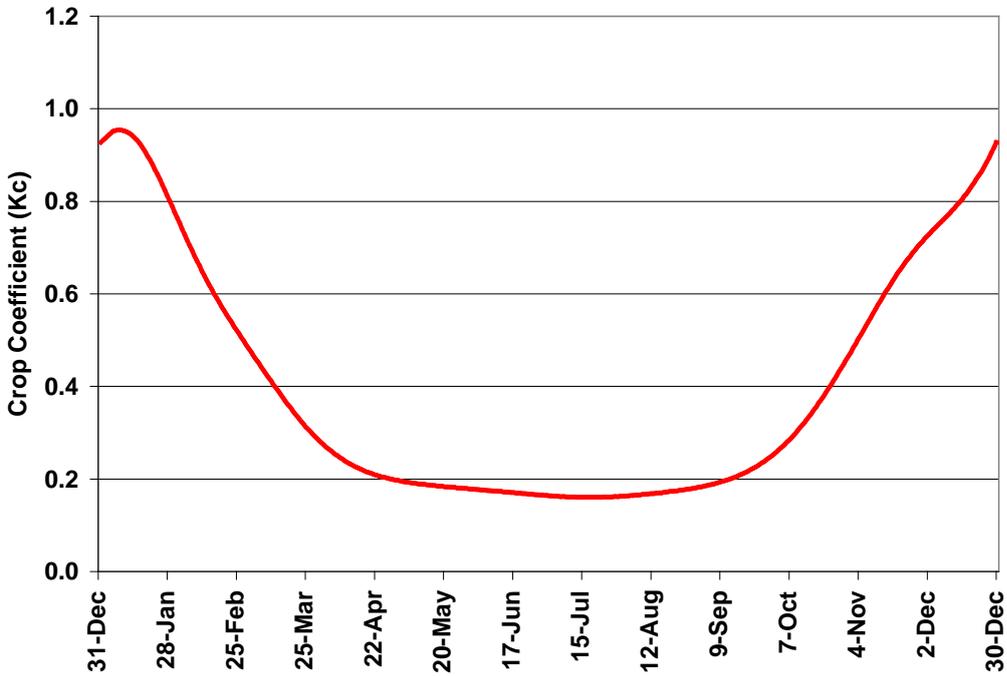


Figure 7. Annual crop coefficient (K_c) curve for near-bare soil from Fig. 6 using the ET_0 and rainfall frequency data in Table 1.

3.4.2 Field and Row Crops

Field and row crops include two main crop types with some sub-types as far as crop coefficients. In this syllabus, crop type-1 includes mainly row crops that are planted and require some time for the crop canopy to develop. There are two sub-types to crop type-1. These are crops that have a declining K_c during late-season and crops that are harvested as fresh market crops that do not have the late-season K_c drop. Type-2 crops include crops that have a full canopy and change their K_c little during the season (e.g., pasture grass and turfgrass).

3.4.2.1 With declining Late Season K_c Values.

Crop coefficients for type-1 crops are determined using a curve like Figure 8 to approximate seasonal changes in K_c values. The season is separated into four growth-and-development periods (1) initial, (2) rapid, (3) mid-season, and (4) late season. The end dates of these periods are assigned the letters A, B, C, D, and E. Date A corresponds to planting, date B to 10% ground shading, date C to 75% or peak ground shading, date D to the onset of senescence, and date E to harvest or defoliation. These growth and development periods and the end dates are used to determine K_c curves.

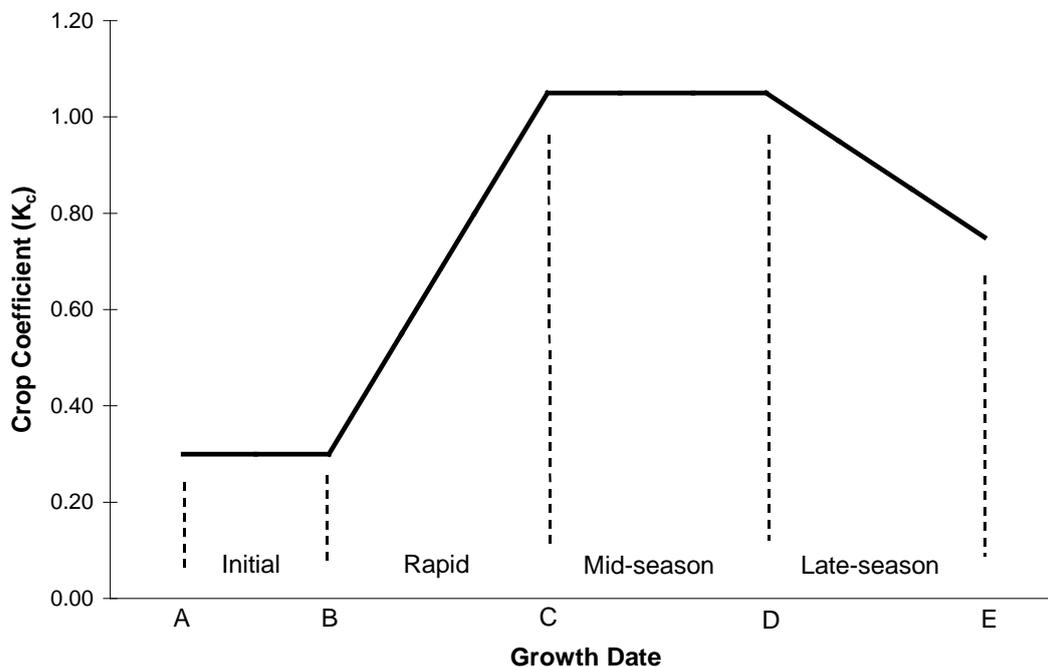


Figure 8. Generalized crop coefficient curve for type-1 field and row crops having a declining K_c during late-season.

K_c factors along with percentages of the season corresponding to each growth period are listed in the CropRef worksheet of the Basic Irrigation Scheduling (BIS) program. K_{c1} is the K_c during initial growth (date A to B), K_{c2} applies during mid-season (date C to D), and K_{c3} is the K_c at harvest or defoliation (date E). The lengths (in number of days) for the

various growth periods vary depending on environmental conditions and the dates must be adjusted. Generally, the number of days within a period increases if the temperature is cooler and decreases if the temperature is higher. However, the percentage of the season for each growth period seems to be relatively conservative. Therefore, if a good estimate for the number of days in the season is available, then the number of days within each period is easily estimated from the percentage of the season attributed to each growth and development period. The percentage values in the CropRef worksheet of BISm can be changed if more site-specific information is available. The original percentage values cannot be changed in the CropRefOrig worksheet of BISm.

Figure 9 illustrates the method for determining a K_c curve for a cotton crop. The off-season K_c values are the same as for bare soil, and the in-season K_c values are determined using Figure 6 for the initial growth period. In this example, a soil wetting frequency of 20-days was used to determine the initial growth K_c value that applies from planting (date A) until 10% ground cover (date B). During May, the $ET_o=5.6 \text{ mm d}^{-1}$ (Table 1), so the K_c during initial growth is about $K_c=0.25$ (Fig. 6). This K_c is only slightly higher than that expected for bare soil (Fig. 9). During the rapid growth period, the K_c value increases linearly from date B to the beginning of the midseason period (date C) where the value (K_{c2}) remains constant until the beginning of senescence (date D). Then the K_c decreases linearly to K_{c3} at the end of the season (date E). This is the approach used to estimate K_c values for most type-1 field and row crops. The values for K_{c2} and K_{c3} are given in the CropRef worksheet of the BISm program. Initially, the value for K_{c1} is set equal to the off-season (bare-soil) K_c value on date A. Then the K_{c1} based on irrigation and rainfall frequency and the ET_o rate is calculated. Finally, the larger of the two values is used for K_{c1} . Similarly, the actual K_{c3} value that is used is the bigger of the K_{c3} value or the off-season (bare-soil) K_c value on date E.

3.4.2.2 Without declining Late Season K_c Values.

Many field crops are harvested before the onset of senescence and therefore do not have declining K_c factors during late season. Figure 10 shows the K_c curve for a fresh-market type-1 crop. The main difference from crops with a declining K_c is that the K_c is constant from date C to date E. Again, personal observation and experiences should be used to estimate the harvest date for determining date E. The K_c values are similar to those for crops with declining late-season K_c values except at the end of the season.

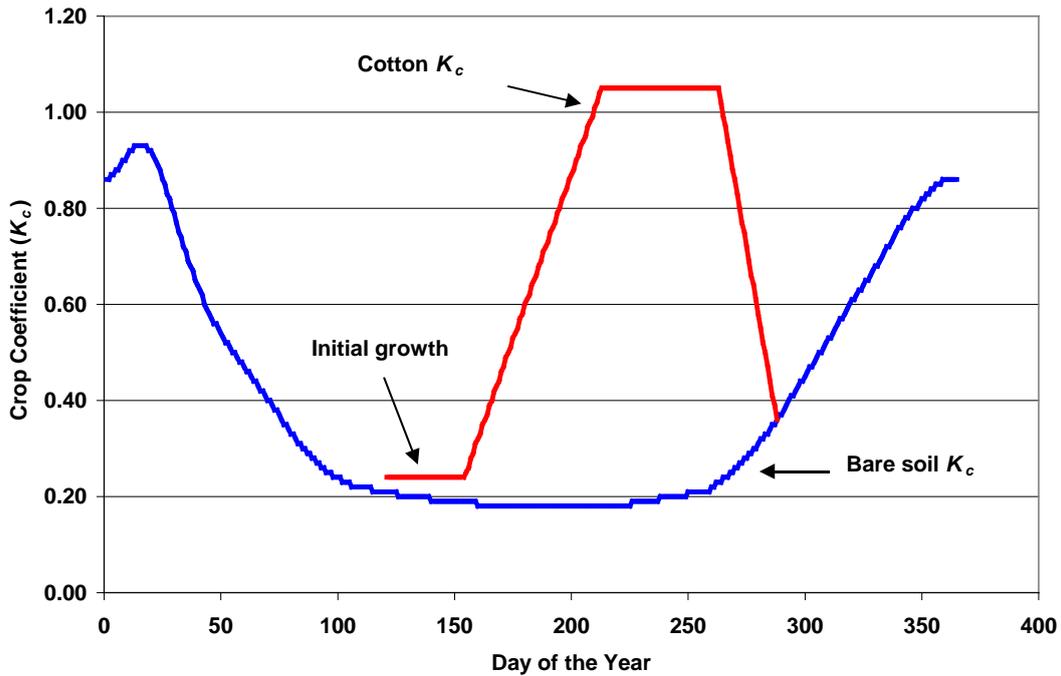


Figure 9. Annual crop coefficient (K_c) curve for cotton with a 20-day irrigation frequency during initial growth. Bare soil K_c values are from Fig. 6 using the ET_o and rainfall frequency data in Table 1.

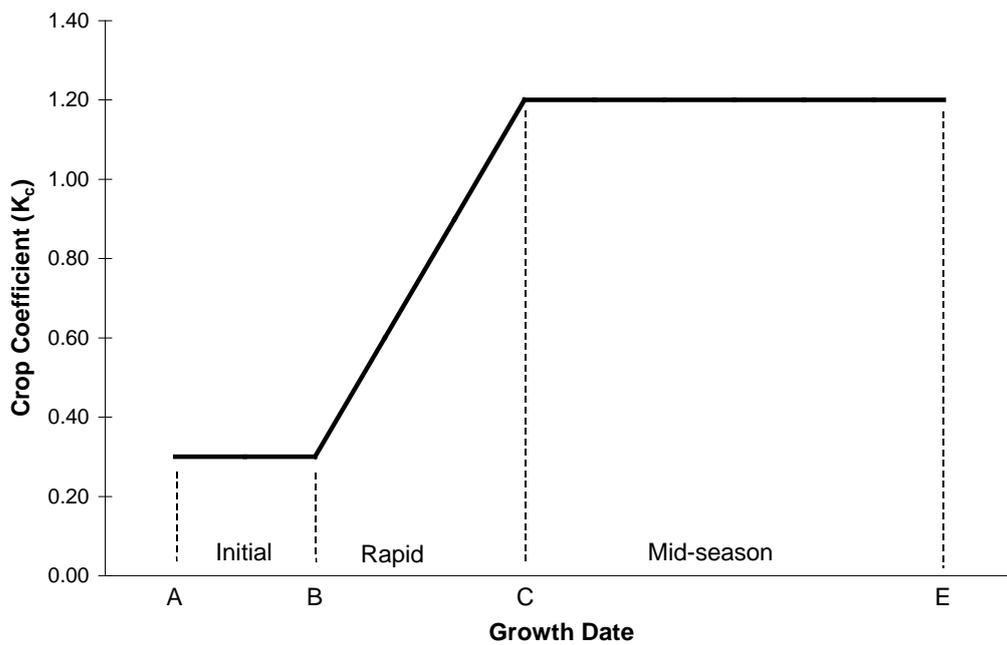


Figure 10. Generalized crop coefficient curve for type-1 field and row crops without a declining K_c during late-season.

3.4.2.3 Field and Row Crops with Fixed K_c Values.

For some crops, the K_c value is essentially fixed during most of the season. These are type-2 field and row crops. Some examples are seasonal estimates for alfalfa, pasture, and turfgrass. Figure 11 shows the annual K_c curve for C-4 species (warm-season) turfgrass and for bare soil. The “in-season” K_c = 0.60, but the off-season K_c is assumed to be equal to the bare soil K_c. A slight over-prediction of ET_c during the off-season might occur because of shading by the dormant grass, but the error is likely to be small because of the low ET_o rates during winter.

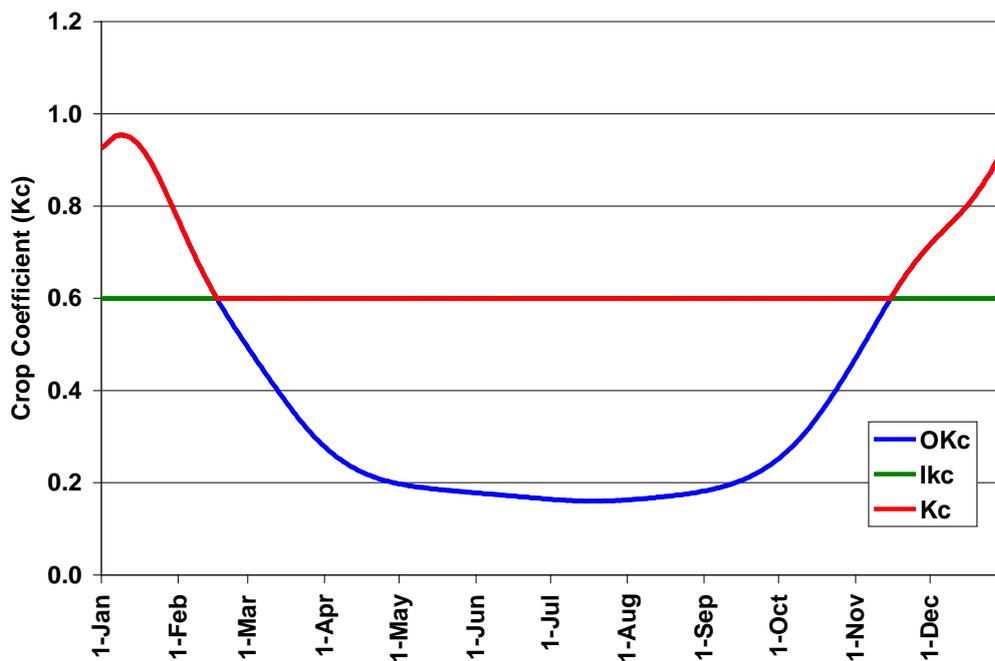


Figure 11. Annual crop coefficient (K_c) for C-4 species turfgrass and bare soil. When the bare soil K_c is higher than the turfgrass K_c = 0.60, the bare soil K_c is used. Bare soil K_c values are from Fig. 6 using the ET_o and rainfall frequency data in Table 1.

3.4.2.4 Mulches and Low Volume (drip) Irrigation.

Many high value vegetable crops are now irrigated with low volume (drip) irrigation systems. Plastic mulches are also widely used. Using mulches and low volume (drip) irrigation during initial growth reduces soil surface evaporation, the ET_c is lowered, and the K_c is smaller. There has been little research on the proper K_c factors to use during initial growth when mulches and low volume systems are employed, but using a frequency of 20 or more days between irrigation or rainfall in Figure 6 provides good estimates.

3.4.3 Deciduous Tree and Vine Crops

3.4.3.1 Mature crops.

Crop coefficients for mature tree and vine crops are determined used in a similar manner as for field crops except there is no initial growth period (Fig. 12). K_c values and growth and development dates from California are given in the CropRef worksheet of the BISM program. The suggested growth and development dates can be changed based on observations and experience. The end dates for growth and development periods are dates B, C, D, and E (Fig. 12). The season begins at leaf out, which corresponds to date B, and ends at leaf drop or after the first hard freeze when the leaves stop transpiring (date E). Date C occurs when the canopy reaches approximately 61% ground cover. The K_c values for deciduous trees and vines are determined in a similar fashion as those described for field and vegetable crops. The K_c on date B and on date E depends on the bare soil evaporation rates on those dates. During the off-season, the K_c values are estimated using the bare soil K_c values. An example for the annual K_c curve for a stone fruit orchard without a cover crop is shown in Fig. 13.

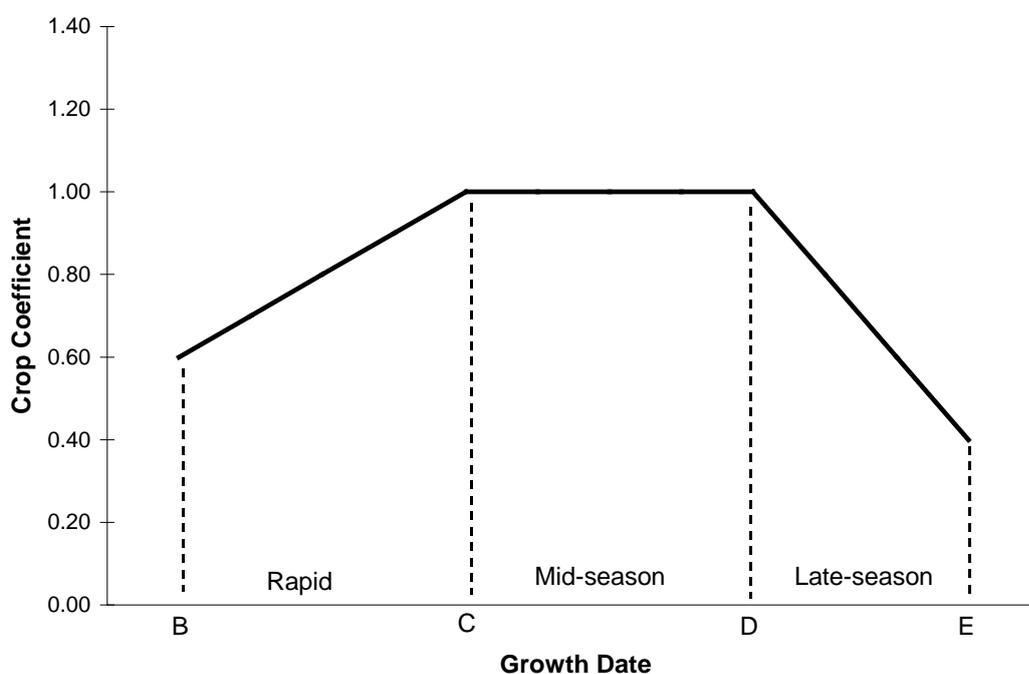


Figure 12. Generalized crop coefficient curve for type-3 tree and vine crops.

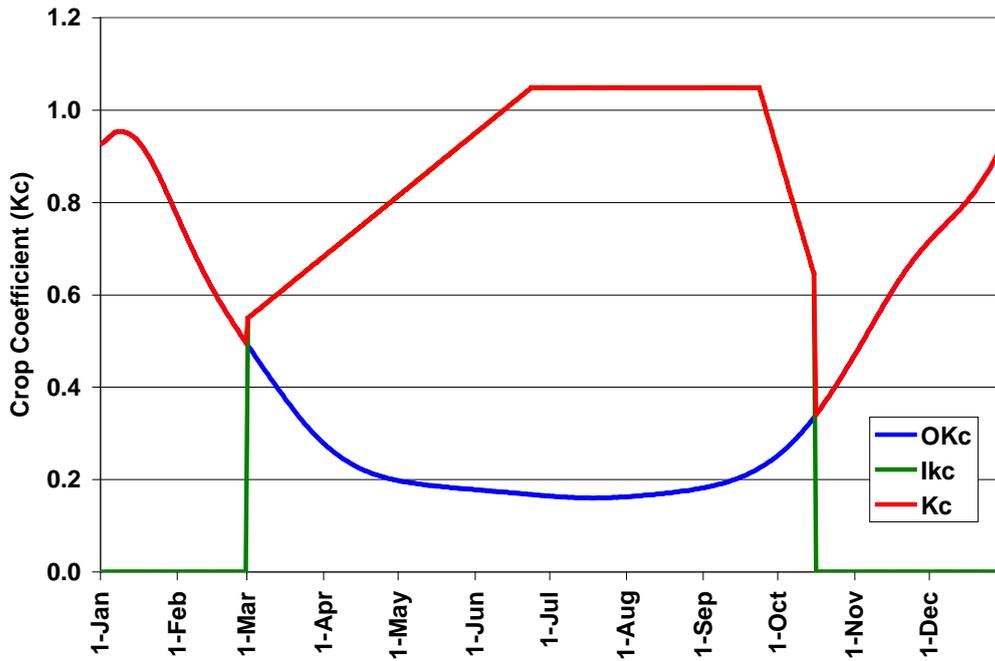


Figure 13. Annual crop coefficient (K_c) for stone fruit orchards without a cover crop. The K_c during the off-season is assumed equal to the bare soil evaporation. Bare soil K_c values are from Fig. 6 using the ET_o and rainfall frequency data in Table 1.

3.4.3.2 Orchards and Vineyards with a Cover Crop.

When a deciduous orchard or vine crop also has a cover crop, the ET_c rate is like to increase up to some maximum value that depends on the evaporative demand. It is assumed that crop will have a minimum $K_c = 0.90$ when a full cover crop is present. However, this K_c can be adjusted if the cover crop is not full and a lower K_c is expected. This assumes that the cover crop will have an ET equal to about 90% of an irrigated pasture (ET_o). The 90% figure is used because the trees or vines will shade the cover crop somewhat and will reduce the ET to about 90% of what it would be if the crop were not present. Once the crop begins to leaf out in the spring (date B), the K_c will increase above $K_{c1}=0.9$. For lack of better information, the rate of K_c increase is the fixed at the same rate as for an orchard or vineyard without a cover crop. However, the K_c value does not increase after the reaching date C or after exceeding $K_c=1.2$, whichever comes first. The maximum K_c value is needed because there is clearly an upper limit for how much energy is available to evaporate water. This maximum value is fixed at $K_{c2} = 1.20$ in this model. This annual K_c curve is shown in Figure 14.

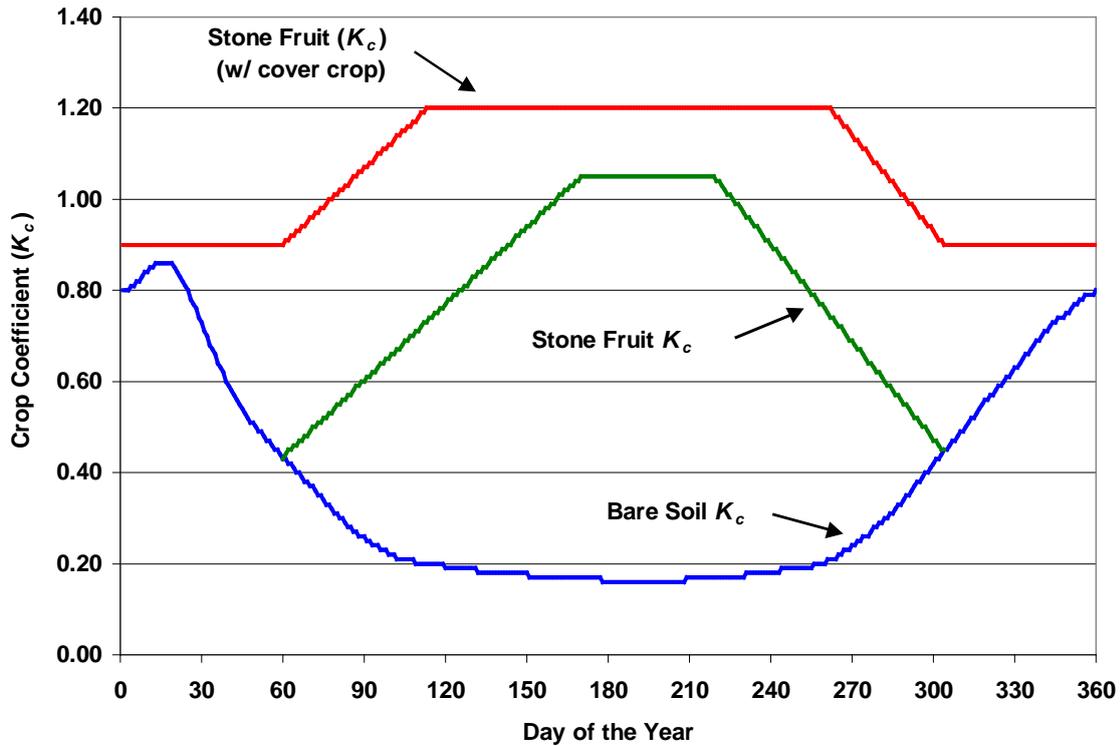


Figure 14. Annual bare soil, stone fruit without cover crop, and stone fruit with cover crop K_c values.

3.4.3.3 Immature Crops.

Immature deciduous trees and vine crops and subtropical and olive orchards use less water than mature crops and the K_c values need adjustment. Figure 15 is used to adjust from a mature to an immature K_c based on the percentage of ground shaded by the canopy. The figure is based on research reported by Fereres (1980) and from Doorenbos and Pruitt (1977). To use the figure, find the percent ground shading on the bottom scale, go up to the curve, and then move horizontally to the left-hand scale to read the multiplication factor to adjust from a mature to an immature K_c . For example, to determine the K_c for a deciduous tree crop with 40% ground shading, the fraction of mature ET_c is 0.80. To determine the K_c , multiply the mature, midseason K_c value by 0.80. For 30% ground shading, the adjustment factor is about 0.65.

Figure 16 shows the annual K_c curved for an immature stone fruit orchard having 35% and 40% ground cover on dates C and D, respectively, without a cover crop. During the off-season, the bare soil K_c values are used and the bare soil K_c values identify the K_c values on dates B and E. The K_c values on dates C and D are estimated using 35% and 40% ground shading in Figure 14. The fraction of mature ET_c from Figure 15 is multiplied by the mature crop K_c to determine the immature crop K_c values on dates B and C. The K_c values are

$K_c=0.72 \times 1.05=0.76$ on date C and $K_c=0.80 \times 1.05=0.84$ on date D. Daily K_c values are determined by linear interpolation between dates B through E.

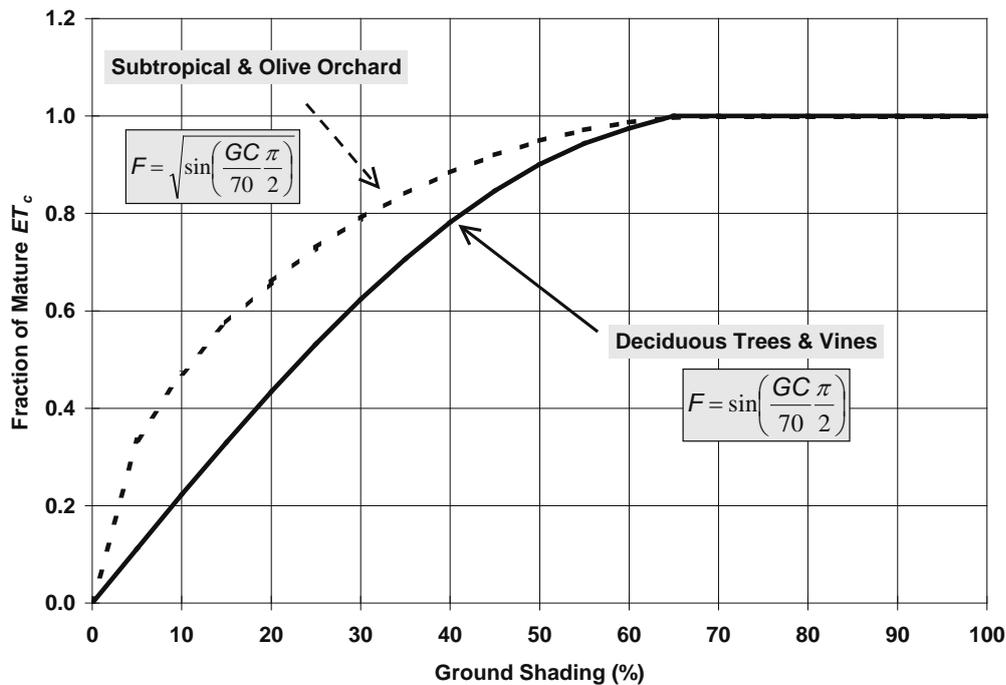


Figure 15. Fraction of mature ET_c for Deciduous Trees and vines and for subtropical and olive orchards as a function of ground shading (%).

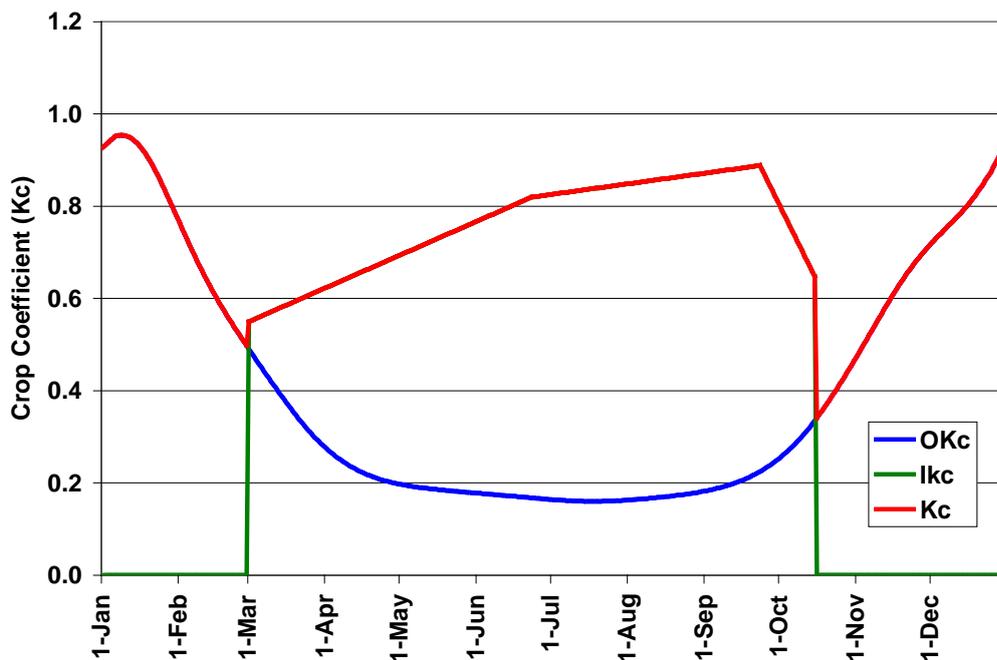


Figure 16. Annual crop coefficient K_c curve for bare soil (blue) and immature stone fruit orchard without a cover crop (red) having 40% ground cover on date C and 45% ground cover on date D. The K_c values on dates C and D are determined as a function of percentage

ground cover using Figure 14. Bare soil K_c values are from Fig. 6 using the ET_o and rainfall frequency data in Table 1.

When a cover crop is present in an immature orchard or vineyard, the K_c values are calculated in a similar fashion as before. The K_c values on dates C and D are determined as a function of percentage ground cover using Figure 14. K_c values between the dates B, C, D, and E, the values are calculated as linear functions of time (days). The minimum K_c for a full cover crop within an orchard or vineyard is assumed to be $K_c = 0.90$ because of shading by the crop. Because of energy limitations, the maximum $K_c=1.20$. From date B to D, the K_c value for a crop with cover is equal to 0.90 plus the difference between the w/o cover K_c for the same date and the K_c on date B up to a maximum of 1.20. From date D to E, the K_c value for an orchard or vineyard with a cover crop is equal to 0.90 plus the difference between the w/o cover K_c for the same date and the K_c on date E but again with a maximum of $K_c = 1.20$. The relationships are shown in Figure 17.

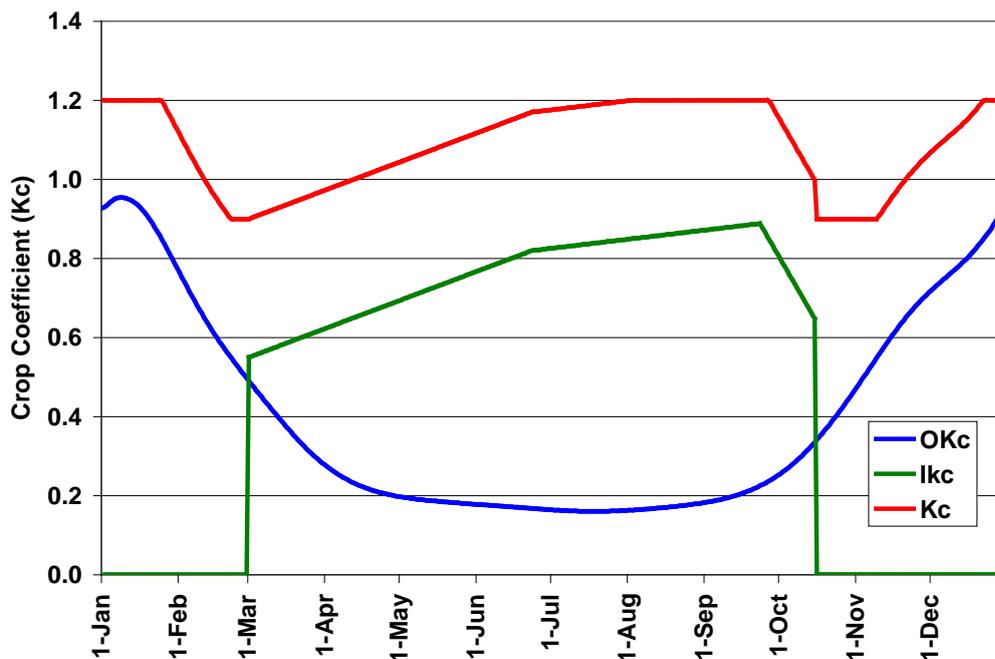


Figure 17. Annual crop coefficient (K_c) curve for bare soil (blue), immature stone fruit orchard w/o cover crop (green), and immature stone fruit orchards with a cover crop (red) having 40% ground cover on date C and 45% ground cover on date D. Bare soil K_c values are from Fig. 6 using the ET_o and rainfall frequency data in Table 1.

3.4.4 Subtropical Tree Crops and Olives

3.4.4.1 Mature Crops.

Mature subtropical and olive trees differ from deciduous trees in that they do not lose their leaves. Consequently, there are only small changes in K_c factors during a year in response to

physiological and environmental factors. In general, the K_c factors are higher during winter when evaporative demand is lower and during periods with considerable leaf drop. A constant K_c factor is employed with little loss in accuracy. The CropRef worksheet of the BISM program includes K_c factors for subtropical tree crops.

Orchard crops that have a fixed K_c value during their full season are type-4 crops. These crops include citrus, olives, etc. that do not lose their leaves. Figure 18 shows the annual K_c curve for mature citrus, with greater than 70% ground shading and no cover crop, grown in the Central Valley of California. If the bare soil K_c were to exceed the citrus K_c , the higher value would be used for the K_c . In this example, the bare soil always had $K_c < 1.0$.

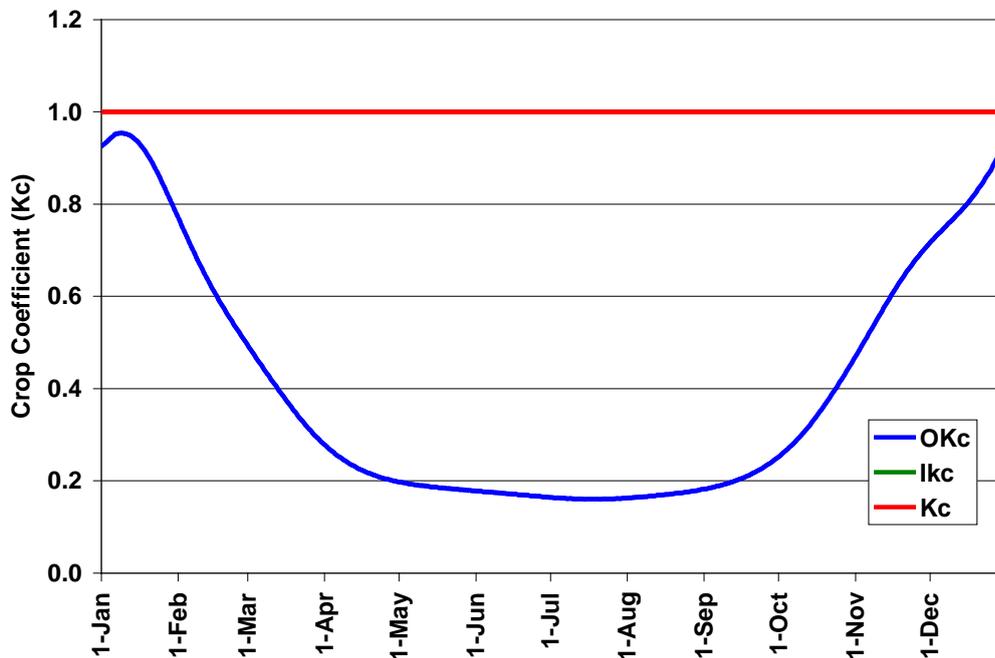


Figure 18. Annual crop coefficient (K_c) for mature citrus grown in Central Valley conditions and K_c values for bare soil. Bare soil K_c values are from Fig. 6 using the ET_o and rainfall frequency data in Table 1.

3.4.4.2 Immature Crops.

Immature crops use less water than mature crops, and the K_c values need adjustment. The dashed line in Fig. 15 is used to adjust the K_c values for percent ground shading. For example, if the mature K_c for citrus is $K_c = 1.00$ and an immature orchard has 30% ground shading, the immature crop has a $K_c = 1.00 \times 0.80 = 0.80$. Figure 15 can also be used to adjust K_c values as the trees grow during a season. Tree or vine spacing can also be a factor affecting the choice of K_c value, and Figure 15 is used to adjust the K_c values.

For immature type-4 orchards, the ground shading and hence the K_c values increase during the year until the crop is mature and exceeds about 70% ground cover. Figure 19

shows the annual K_c curve for an immature citrus crop and no cover crop. The K_c values on dates B, C, D and E were determined using Fig. 14. The K_c values for an immature crop are calculated as the product of the adjustment from Fig. 15 and the mature crop K_c . For a crop attaining 25%, 30%, 40%, and 45% ground shading on dates B, C, D, and E, the K_c values are approximately $K_c = 1.00 \times 0.73 = 0.73$, $K_c = 1.00 \times 0.79 = 0.79$, $K_c = 1.00 \times 0.88 = 0.88$, and $K_c = 1.00 \times 0.92 = 0.92$, respectively. Date B falls on 1 January, and date E is on 31 December. Date C occurs at 33% of the season (1 May), and date D occurs at 67% of the season (2 September). Intermediate K_c values are determined with a linear trend between dates. If the bare soil K_c exceeds the citrus K_c , the higher value is used for the K_c . This is shown in Fig. 19 where the bare soil K_c , based on rainfall and ET_o rate, is higher than the orchard K_c during the winter season.

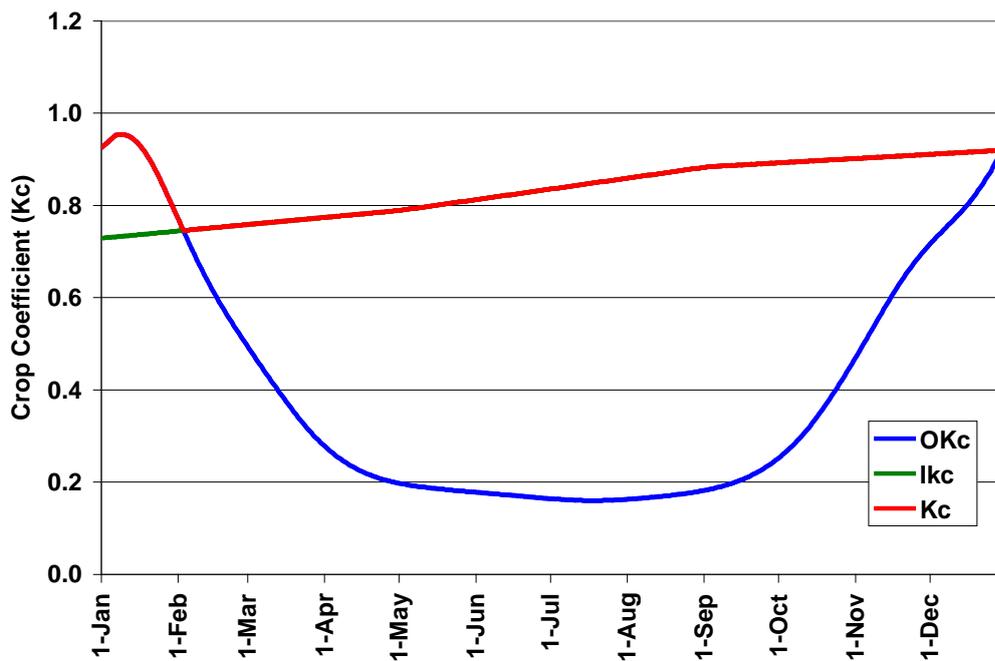


Figure 19. Annual crop coefficient (K_c) curve for immature citrus having ground cover equal to 25%, 30%, 40%, and 45% on dates B, C, D, and E, respectively. Bare soil K_c values are from Fig. 6 using the ET_o and rainfall frequency data in Table 1.

3.4.4.3 Between Row Ground Cover.

When a ground cover is present, a higher K_c is needed. The K_c value should fall somewhere between the value without ground cover and the maximum K_c or $K_c = 1.0$, whichever is higher, depending on the extent of ground cover. For example, if a mature citrus crop without ground cover has $K_c = 0.65$, a crop with a full grass cover should have a K_c near $K_c = 1.0$. If the vegetation does not completely cover the ground, a lower K_c value should be used.

3.4.4.4 Drought Strategies.

Recent reports on drought strategies for deciduous trees (Goldhamer, 1989) report that some trees can be stressed during portions of the season without adversely affecting production. In general, stress should be avoided when fruiting buds are set for the following year. If water supplies are inadequate, additional stress factors can be employed to adjust the ET_c estimates for stress during tolerant periods.

3.4.4.5 Mulches and Low Volume (drip) Irrigation.

Many high value vegetable crops are now irrigated with low volume (drip) irrigation systems. Plastic mulches are also widely used. Using mulches and low volume (drip) irrigation during initial growth reduces soil surface evaporation, the ET_c is lowered, and the K_c is smaller. Little research exists on the proper K_c factors to use during initial growth when mulches and low volume systems are employed, but using a frequency of 20-30 days between irrigation or rainfall in Figure 9 provides reasonably accurate estimates.

3.4.5 Other Evaporating Surfaces

Evaporation from other surfaces than crops is determined by multiplying ET_o by a coefficient (K_c). A listing of K_c values for various surfaces is given in the Basic Irrigation Scheduling (BISm) program.

3.5 Effective Rainfall

Estimating effective rainfall (R) accurately requires prior knowledge of the soil water content within a crop root zone and, when there is intense rainfall, a reliable estimate of surface runoff. To know the daily soil water content, water balance calculations are needed. Generally, the ET approach to calculating the soil water content is better than field monitoring for estimating effective rainfall because water content values are determined on a daily basis. Effective rainfall is estimated by balancing all of the sources and losses of water.

Rainfall that wets the plant surfaces and that is stored in the crop's effective root zone is effective rainfall (rainfall that contributes to crop evapotranspiration). During the growing season, crop evapotranspiration (ET_c) from an irrigated field is mainly limited by the energy available to evaporate the water. Therefore, it is possible to accurately estimate ET_c and changes in soil water content using energy balance calculations. It is more difficult to determine ET from bare soil during the off-season because soil properties and rainfall frequency, duration, and amount influence evaporation rates. Consequently, using ET to keep a water balance and to estimate effective rainfall is recommended only during the growing season. To know the beginning soil water content, a soil water content measurement or pre-irrigation to field capacity is recommended

Effective rainfall (R) is determined by considering the measured rainfall (P), surface runoff (Q), soil water content at field capacity (FC), and the root zone soil water content (SWC) before the rainfall. Surface runoff can be calculated using the USDA-Soil Conservation Service (SCS) curve number (CN) method or it can be visually estimated. Generally, a visual estimate of runoff is sufficient in locations where the “in-season” rainfall is typically light. Use of the CN method is recommended only where detailed estimates are required.

Soil water depletion SWD before rainfall is calculated as the difference between the water content at field capacity and the root zone water content ($SWD=FC-SWC$). Because field capacity is not a well-defined soil characteristic, gravitational water in the soil (between field capacity and saturation) is ignored in effective rainfall calculations. Therefore, the actual effective rainfall may be slightly underestimated. Assuming that the water infiltrated into the soil in excess of SWD is lost to deep percolation, SWD is the maximum possible value for effective rainfall. FC is estimated from soil water holding characteristics and knowledge of the crop rooting depth. SWC is determined using a daily water balance (ETc) calculation.

There are two cases to consider when estimating effective rainfall. If the measured rainfall (P) minus the runoff (Q) is greater than or equal to SWD before rainfall, then the effective rainfall (R) equals SWD.

$$R = SWD \quad \text{if } P - Q \geq SWD \quad (37)$$

If the total rainfall minus the runoff is less than SWD, then the effective rainfall equals the total rainfall minus the runoff.

$$R = P - Q \quad \text{if } P - Q < SWD \quad (38)$$

Runoff depends on the crop, soil type, antecedent soil moisture conditions, slope of the land, cultural practices, etc. However, when rain-storms are light and surface runoff is insignificant, effective rainfall can be estimated, during a cropping season, using the following equations.

$$R = SWD \quad \text{if } P \geq SWD \quad (39)$$

And

$$R = P \quad \text{if } P < SWD \quad (40)$$

The main problem in estimating effective rainfall is to know SWD before the rainfall occurs. Therefore, a daily soil water balance calculation or soil water content measurement prior to the rainfall event is needed to accurately estimate effective rainfall.

3.6 Stored Soil Water

Initial soil water deficit (ISWD) and the final SWD (on date E) are used to determine the stored soil water contribution to the seasonal water needs of a crop. An irrigated field typically begins a season ISWD ≈ 0 (initial SWC \approx FC) and normally ends the season with the SWD near the PWP. The difference between these two water contents is the seasonal stored soil water that contributes to the crop water needs. What happens between the beginning and end of the season can affect the contribution from stored soil water, but the potential contribution is only limited by the soil's water holding capacity and acceptable water content at the end of the season. The goal of good irrigation scheduling is to use as much of the stored soil water as possible without hurting the marketable yield. For example, a crop starting the season with an ISWD = 0 and ending the season with the SWD = 70 mm has 70 mm of contribution from preseason stored water.

3.7 Fog Interception

ET estimates are affected by the presence of fog because of effects on radiation, temperature, humidity, etc., but these effects are considered in the calculation of ET_o . However, when fog passes through a crop, some water is intercepted by and coats the plant leaves. Fog interception is like a light rainfall, and it should be considered in water balance calculations like effective rainfall. Evaporation of fog interception comprises part of the crop ET and reduces the amount of water withdrawn from the soil. In situations where the ET rate is low, fog interception can supply a large portion of the water needs of a crop. An approximation for the contribution of fog to ET_c is possible using Fig. 20, which shows the fraction of daily ET_c supplied by fog interception as a function of the roughly estimated time of day when the water dries from the crop leaves.

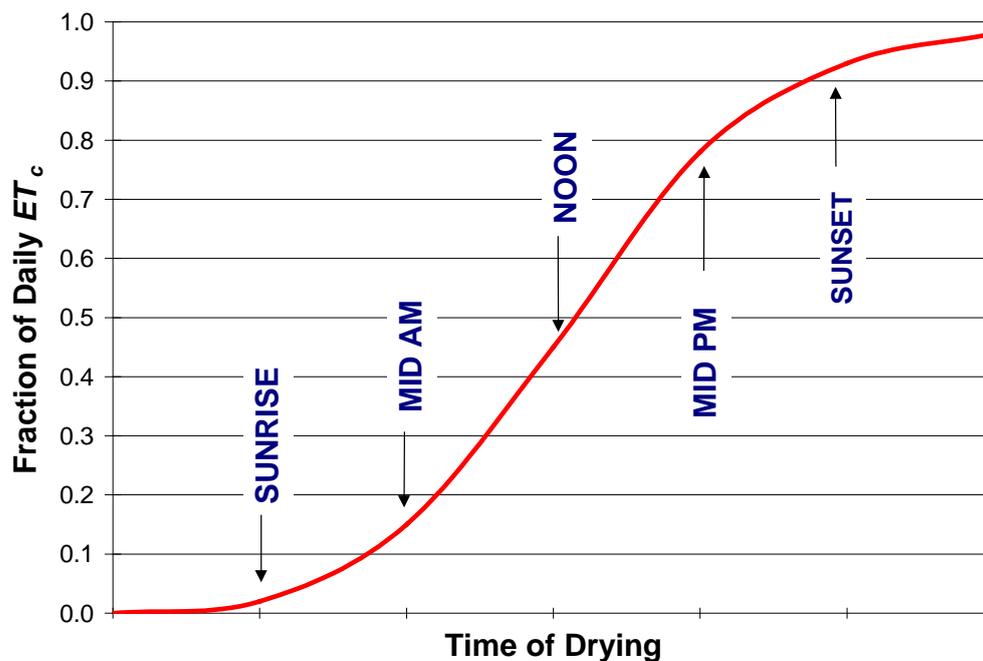


Figure 20. Plot of the fraction of daily ET_c as a function of time when fog interception mostly dries from the canopy.

As an example of fog contribution calculations, assume that fog interception dries off the leaves of a crop at mid-morning on a day with $ET_c = 5$ mm. The contribution of fog interception (C_F) is calculated as $C_F = 0.15 \times 5 = 0.75$ mm. If the fog interception was observed to dry off at noon rather than mid-morning, the contribution of fog interception would be $C_F = 0.45 \times 5 = 2.25$ mm.

3.8 Irrigation Scheduling

Irrigation is used to replace soil water losses that are not replaced by natural means (i.e., rainfall, fog interception, and water table). Applications are normally timed to replace water before yield-reducing water stress occurs. Water losses occur mainly through crop evapotranspiration (ET_c) and exact estimates of ET_c are needed to accurately determine soil water depletion. Careful ET_c estimates are especially important for efficient irrigation management of low-volume (i.e., drip and micro-sprinkler) and sprinkler irrigation systems. The first step in irrigation scheduling is to determine a schedule based on historical data. Often a schedule based on historical ET_o provides considerable benefit for little effort. Therefore, derivation of historical ET_o schedules is highly recommended.

Crop evapotranspiration depends on the weather and on plant and management factors. Assuming there is no plant stress, the actual evapotranspiration (ET_a) is at a maximum value (ET_c). If properly irrigated, most crops will have the maximum evapotranspiration $ET_c = ET_o \times K_c$. In some cases, crops are purposely water stressed to reduce vegetative growth (i.e., cotton), increase partitioning of photosynthate to the harvested parts (i.e., sugarbeets), reduce water accumulation in the harvested product (i.e., tomatoes), or to enhance crop quality (i.e., wine grapes). If a crop is purposely stressed, an additional stress factor (K_s) may be needed to adjust ET_c to ET_a . It is important to remember that crop coefficients are used to determine ET_c not ET_a .

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Appendix

Table A.1. Water holding capacity* (cm/cm depth of soil) of main texture groups. Figures are averages and vary with structure and organic matter differences.

Soil Texture	Field Capacity (θ_F)	Wilting Point (θ_P)	Available Water (θ_A)
Coarse sand	0.06	0.02	0.04
Fine sand	0.10	0.04	0.06
Loamy sand	0.14	0.06	0.08
Sandy loam	0.20	0.08	0.12
Light sandy clay loam	0.23	0.10	0.13
Loam	0.27	0.12	0.15
Sandy clay loam	0.28	0.13	0.15
Clay loam	0.32	0.14	0.18
Clay	0.40	0.25	0.15
Self-mulching clay	0.45	0.25	0.20

***Source: United States Department of Agriculture Bulletin 462, 1960**